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NCT Report No. 3789/607

Advanced Tribological  
Coatings For High Specific  
Strength Alloys,  
R&D 5876-MS-01

Contract DAJ A45-87-C-004

5th Interim Report

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# National Centre of Tribology

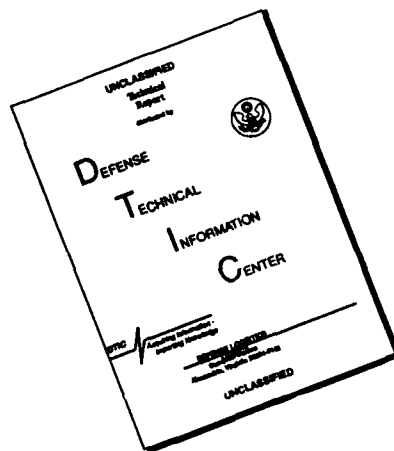
Risley Nuclear Power  
Development Laboratories



NCT

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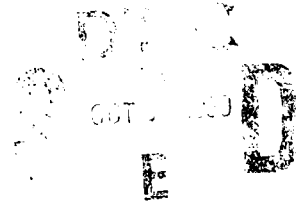
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UNITED KINGDOM



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## CONTENTS

1. INTRODUCTION
2. SURFACE TREATMENTS PERFORMED
3. SURFACE ROUGHNESS MEASUREMENTS
4. METALLOGRAPHIC EXAMINATION
  - 4.1 Coating Thickness
  - 4.2 Microhardness/Depth Profile
5. FRICTION AND WEAR MEASUREMENTS
  - 5.1 Test Conditions
  - 5.2 Results at 20N Load
  - 5.3 Results at 50N Load
6. DISCUSSION & FURTHER WORK PLANNED

Figures 1 - 10

- APPENDIX 1: Scanning Electron Micrographs  
APPENDIX 2: Optical Micrographs  
APPENDIX 3: Microhardness Depth Profiles  
APPENDIX 4: 20N Wear Profiles and SEM Micrographs of Wear Tracks  
APPENDIX 5: 50N Wear Profiles and SEM Micrographs of Wear Tracks



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## 1. INTRODUCTION

This 5th interim report summarises the work performed to date on the US Army contract 'Advanced Tribological Coatings for High Specific Strength Substrates'. The objective of this contract are to develop and test a surface treatment suitable for the hardening of a titanium alloy precision gear for use in a vacuum environment.

Attention has been primarily directed at surface hardening by the interstitial diffusion of the elements nitrogen, oxygen and carbon. Targets of a surface hardness of >500 HV and depth 50 microns, without the need of any post heat treatment operations have been identified.

## 2. SURFACE TREATMENTS

The surface treatments under study have been applied to specimens of IMI 318 (Ti6Al4V), cut from plate. The sample numbers and corresponding surface treatments which have been carried out and tested to date are listed in Table 1 below. 'SHT' indicates that the plates sample was in a solution heat treated condition before surface treatment. 'H&G' indicates that the sample was in a hardened and ground condition before surface treatment.

Surface roughness measurements taken before and after treatment. Thickness measurements taken before and after treatment. Photo-micrographs taken before and after treatment.

Table 1: Sample Number Allocated to Surface Treatments.

Sample Number	Surface Treatment
HSSA1	Solution Heat Treated
HSSA2	Hardened and Ground
HSSA3	(SHT) Plasma Nitrocarburized 1
HSSA4	(SHT) Beta Nitrocarburized
HSSA5	(SHT) Ion Implanted (N <sup>+</sup> ) 1
HSSA6	(H&G) Ion Implanted (N <sup>+</sup> ) 2
HSSA7	(SHT) Hard Anodised 1
HSSA8	(H&G) Hard Anodised 2
HSSA9	(SHT) Plasma Nitrocarburized 2
HSSA10	(SHT) Hard Anodised 3
HSSA11	(H&G) Hard Anodised 4
HSSA12	(SHT) Plasma Nitrided 1
HSSA13	(H&G) Plasma Nitrided 2
HSSA14	(SHT) High Temperature Nitrocarburized 1
HSSA15	(H&G) Nitrox 1
HSSA16	(SHT) Pack Aluminising 1
HSSA17	(SHT) Nitrox 2
HSSA18	(H&G) Nitrox 3
HSSA19	(SHT) Pack Aluminising 2
HSSA20	(SHT) Gas Carbonitriding 1
HSSA21	(SHT) Diamond-like Carbon (DLC) 1
HSSA22	(SHT) TiN Reactive Sputter
HSSA23	(SHT) TiN/HfN Multilayer
HSSA24	(SHT) Pack Aluminising 3

### 3. SURFACE ROUGHNESS MEASUREMENTS

For the application of dry lubricants (ie sputtered  $\text{MoS}_2$ ) onto hardened titanium alloy gears, the surface roughness is an important parameter in determining film (and hence gear life). The surface roughness of all the sample plates were, therefore, measured using a Talysurf 6 profilometer, and the values of  $R_a$ , Delta-Q and  $R_{sk}$  recorded. These parameters are defined as:

$R_a$ : The arithmetic mean of the departure of the roughness profile from the mean line (in micrometres).

Delta-Q: The RMS slope of the profile throughout the assessment length (in degrees).

$R_{sk}$ : The measure of the symmetry of the profile about the mean line (in degrees).  $R_{sk}$  will distinguish between asymmetric profiles which have the same  $R_a$  value.

The surface roughness measurements for the samples are summarised in Figure 1. This figure has been arranged with the samples that were originally solution heat treated grouped first, followed by those which were originally hardened and ground. Essentially only pack aluminising (HSSA19) causes any detriment to the surface roughness, all other treatments either cause no change or a small improvement in the surface roughness.

### 4. METALLOGRAPHIC EXAMINATION

Optical metallographic specimens were prepared by nickel coating a small piece of each sample and embedding this in thermosetting resin. Each specimen was then ground and polished to produce a section through the sample at  $90^\circ$  to the hardened surface. From this section, coating structure and thickness could be ascertained, and a microhardness depth profile measured.

#### 4.1 Coating Thickness

The micrographs from the metallographic examination of the samples, with the exception of HSSA10 are included in Appendix 2. From the micrographs the resulting coating thickness was determined and are given in table 2 below.

Table 2: Surface Treatment Coating Thickness & Hardness.

Sample	Surface Treatment	Coating Thickness	Hardness
HSSA1	Solution Heat Treated	not applicable	
HSSA2	Hardened and Ground	not applicable	
HSSA3	Plasma Nitrocarburized 1	<2 micrometres	Not measured
HSSA4	Beta Nitrocarburized	5-10 micrometres	550 Hv
HSSA5	Ion Implanted (N <sup>+</sup> ) 1	negligible	Not measured
HSSA6	Ion Implanted (N <sup>+</sup> ) 2	negligible	Not measured
HSSA7	Hard Anodised 1	negligible	Not measured
HSSA8	Hard Anodised 2	negligible	Not measured
HSSA9	Plasma Nitrocarburized 2	negligible	Not measured
HSSA10	Hard Anodised 3	negligible	Not measured
HSSA11	Hard Anodised 4	negligible	Not measured
HSSA12	Plasma Nitrided 1	<1 micrometre	Not measured
HSSA13	Plasma Nitrided 2	negligible	Not measured
HSSA14	High Temp Nitrocarburized	<2 micrometres	Not measured
HSSA15	Nitrox 1	-5 micrometres	-400 Hv
HSSA16	Pack Aluminising 1	25 micrometres	360 Hv
HSSA17	Nitrox 2	negligible	Not measured
HSSA18	Nitrox 3	low micrometres	-400 Hv
HSSA19	Pack Aluminising 2	25 micrometres	<400 Hv
HSSA20	Gas Carbonitriding 1	50 micrometres	700 Hv
HSSA21	Diamond-like Carbon 1	1 micrometre	Not measured
HSSA22	TiN Reactive Sputter	3 micrometres	Not measured
HSSA23	TiN/HfN Multilayer	5 micrometres	Not measured
HSSA24	Pack Aluminising 3	27 micrometres	560 Hv

#### 4.2 Microhardness Depth Profile

Microhardness depth profiles were produced by measuring the Vickers microhardness at increasing depth into the sample on the metallographic specimens. The hardness was measured by applying a load of 50N for 15 seconds. The microhardness profiles are summarised in Appendix 3.



## 5. FRICTION AND WEAR MEASUREMENTS

To identify the most promising surface treatments from the large number of samples (for more detailed friction & wear evaluation in vacuum and for rolling contact surface fatigue assessment), the friction and wear of all samples was evaluated at two load conditions on a reciprocating tribometer at NCT. All these 'screening' tests were performed in air; any sample performing poorly in air would be very unlikely to perform well under vacuum conditions.

### 5.1 Test Conditions

The reciprocating tribometer was set to give a 20 mm stroke, with 500 cycles per test, giving a cumulative sliding distance of 20 metres. Tests were performed at two different loads (20 & 50N, equivalent to maximum Hertzian contact stresses of 1.30 & 1.76 Mpa respectively). The loads were applied using hardened En31 steel balls in contact with the treated titanium alloy plate. Both balls and plate samples were ultrasonically cleaned before test and no lubricant was added. Frictional forces were recorded continuously on a chart recorder.

Wear profiles and the volume of material removed from the specimens was measured using a 3D surface profilometer. All the wear scars were photographed at x50 in a SEM at 20kV using Secondary Electron Imaging (SEI), with additional photographs taken as needed at other magnifications and accelerating voltages, using both SEI and Back Scattered Imaging (BSI).

### 5.2 Results at 20N Load

Figures 2 and 3 summarise the friction (at various test intervals) and the measured wear rates. The wear profiles, with attached SEM micrographs of the central region of the scars, with the exception of HSSA16, are contained in Appendix 4.

Samples HSSA1 & HSSA2 can be regarded as the baseline performance, any coating exhibiting high friction or wear can be rejected from further study. At this load samples HSSA4, HSSA10, HSSA11, HSSA14, HSSA20 to HSSA 23 show 'good' performance. The extent of the wear on HSSA4, HSSA20 and HSSA24 is not readily apparent in the micrographs attached to the wear profiles. The scars show up more clearly when viewed in back

scattered image (Figure 4). The TiN/HfN multilayer coating of HSSA23 appears to have started to break up during this test (Figure 5).

### 5.3 Results at 50N Load

Figures 6 and 7 show the friction (at various test intervals) and the measured wear rates. The wear profiles, with attached SEM micrographs of the central region of the scars, with the exception of HSSA16, are contained in Appendix 5.

Samples HSSA4, HSSA14, HSSA20 & HSSA 22 give low wear rates and reasonable friction coefficients. SEM analysis revealed metal transfer from the En 31 ball to the plate occurred during the test on HSSA4 (Figure 8). A small hole can be seen in the coating of sample HSSA 22 which may indicate that the coating is starting to break up (Figure 9).

### 6. DISCUSSION & FURTHER WORK PLANNED

To date samples HSSA4, HSSA14, HSSA20 & HSSA22 show the most promising friction and wear performance. Sample HSSA20 also meets the targets for surface hardness and treatment depth

Analysis of the plasma nitrided samples (HSSA12 and HSSA13) has revealed poor processing, further samples are being prepared with a different supplier. The TiN/HfN multilayer (HSSA23) probably failed at 50N because substrate could not support the coating (cf ice on mud). The wear rate for this treatment is greater than that for uncoated titanium because of the presence of TiN and HfN particles in the wear debris. These are very hard and effectively improve the cutting properties of the En30 ball. Multi-treatment (e.g. Nitrocarburize then TiN/HfN multilayer) would result in support for the film and improved results. This approach is being evaluated.

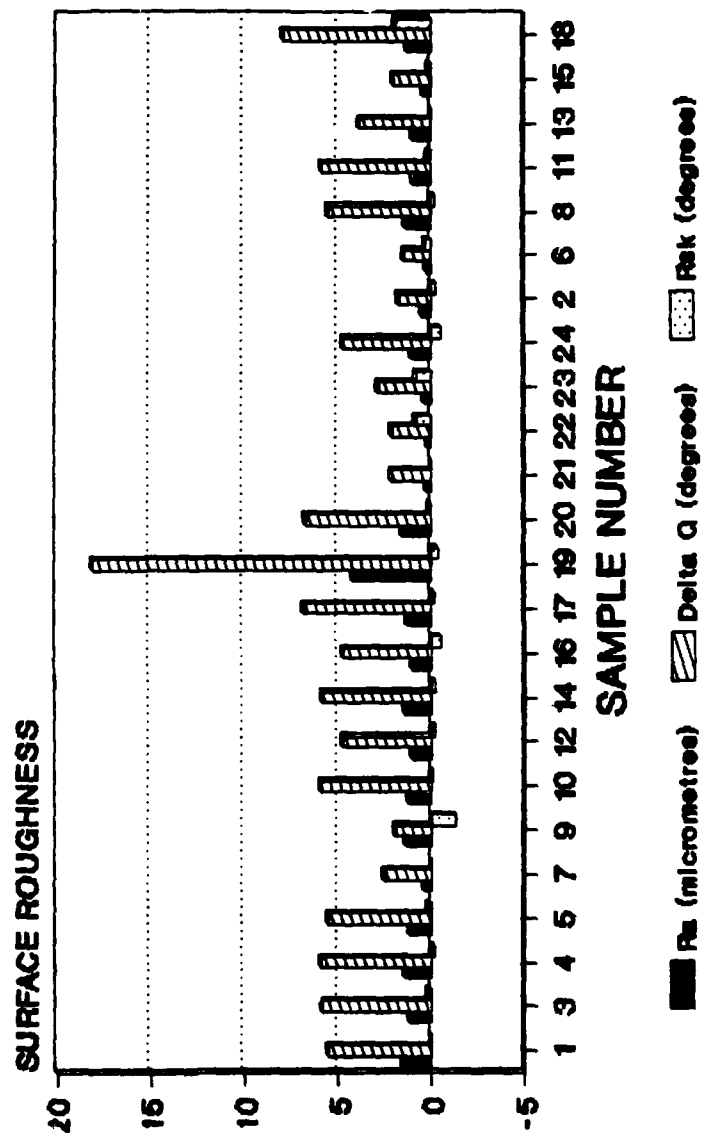
Further work is aimed at measuring the friction and wear performance of samples HSSA1, HSSA2, HSSA4, HSSA14, HSSA20 and HSSA22 at a load of 250N (3 GPa). This is the maximum achievable on the NCT reciprocating tribometer.

Sample HSSA26 (High Temperature Plasma Nitriding) has recently arrived, and is currently undergoing metallographic examination. The remaining samples are still with the

coating/surface treatment companies.

All test items for the NCT vacuum test rig and rolling contact fatigue specimens have been manufactured. After completion of the 250N tests, the fatigue specimens will be sent for treatment and then forwarded to AMTL for evaluation.

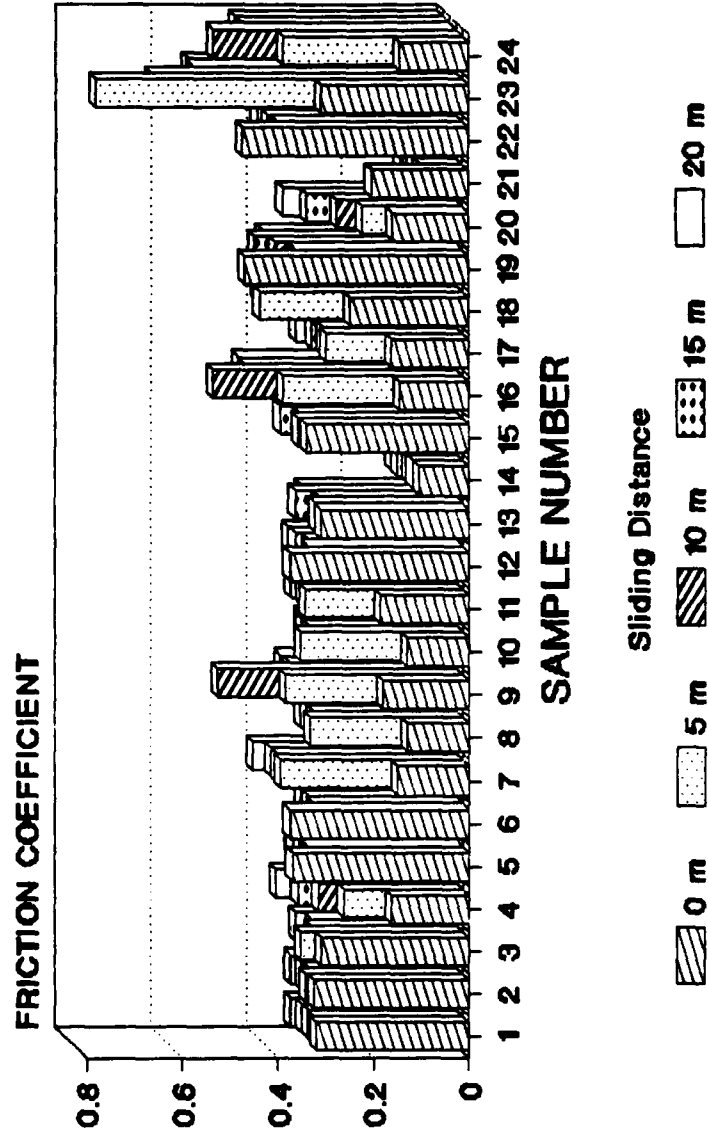
# **HSSA RECIPROCATING WEAR TESTS** **SURFACE ROUGHNESS MEASUREMENTS**



NATIONAL CENTRE OF TRIBOLOGY

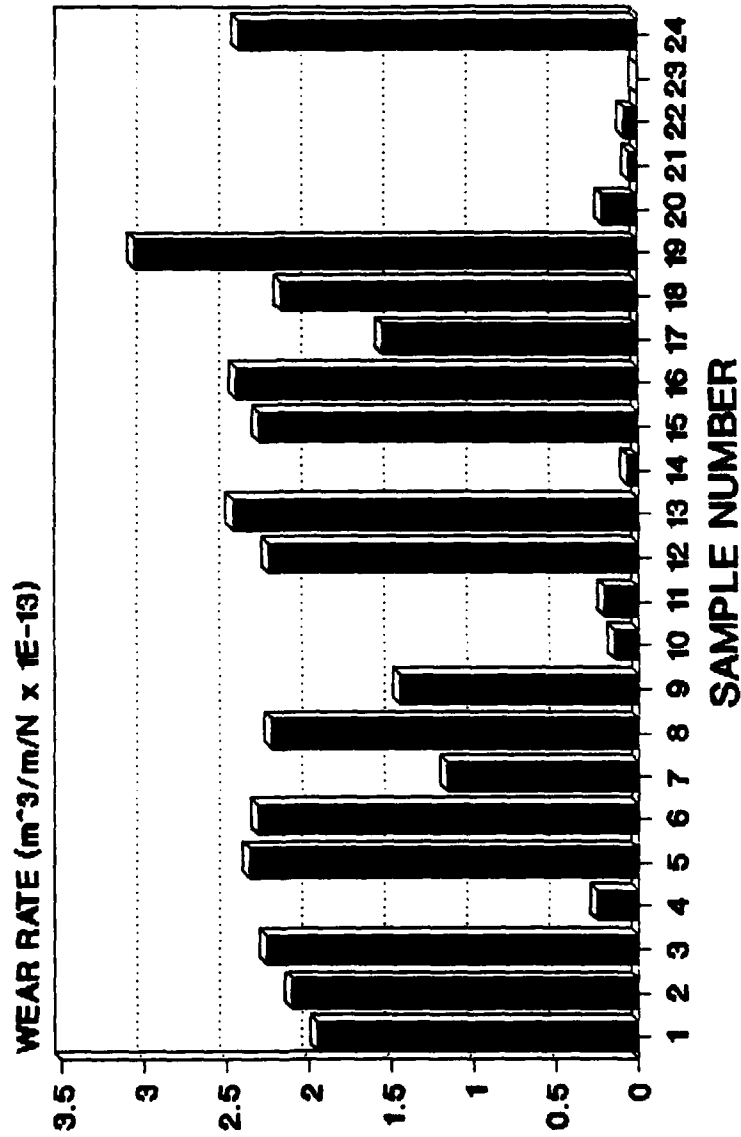
# HSSA RECIPROCATING WEAR TESTS

20 N LOAD, IN AIR, 1.3 GPa (MAX)



NATIONAL CENTRE OF TRIBOLOGY

# **HSSA RECIPROCATING WEAR TESTS** **20 N LOAD, IN AIR, 1.3 GPa (MAX)**



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HSSA 4

HSSA 20

HSSA 24

Figure 4: x50, 20kV Accelerating Voltage  
Back Scattered Image

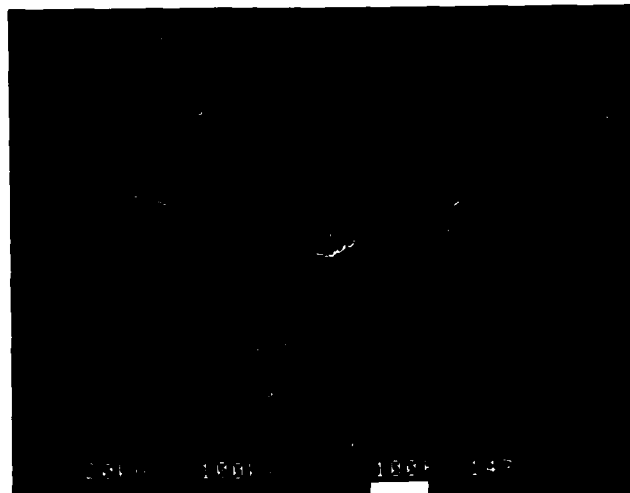
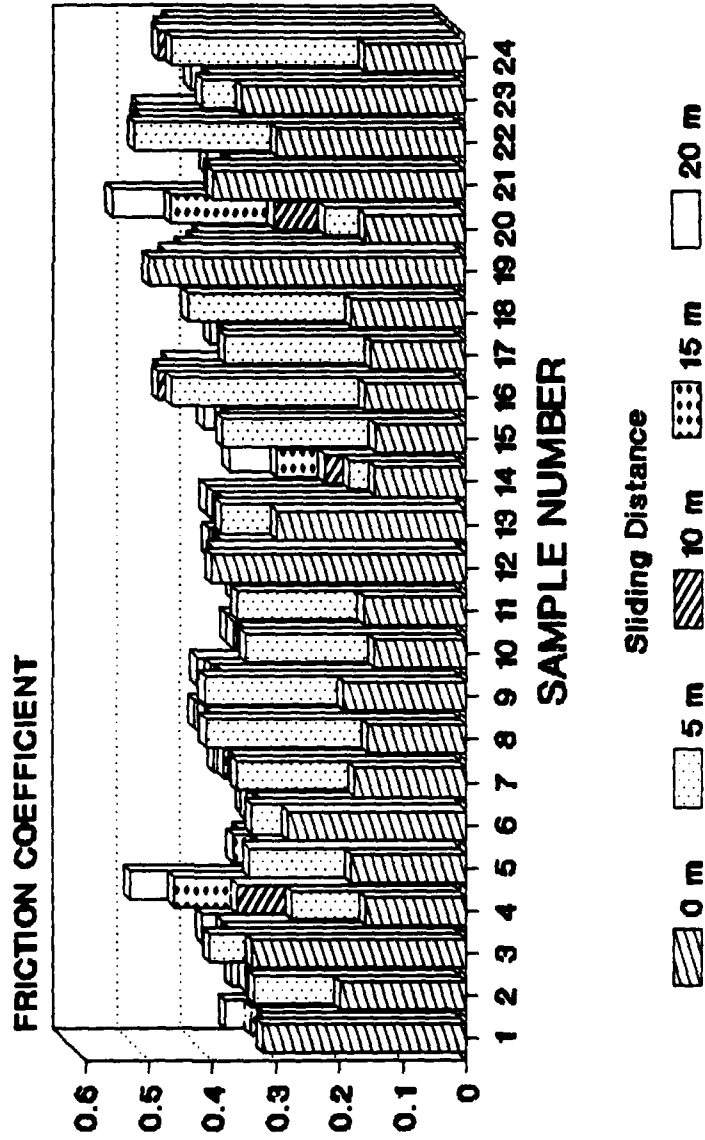


Figure 5: HSSA23: Coating damage at 20N load.



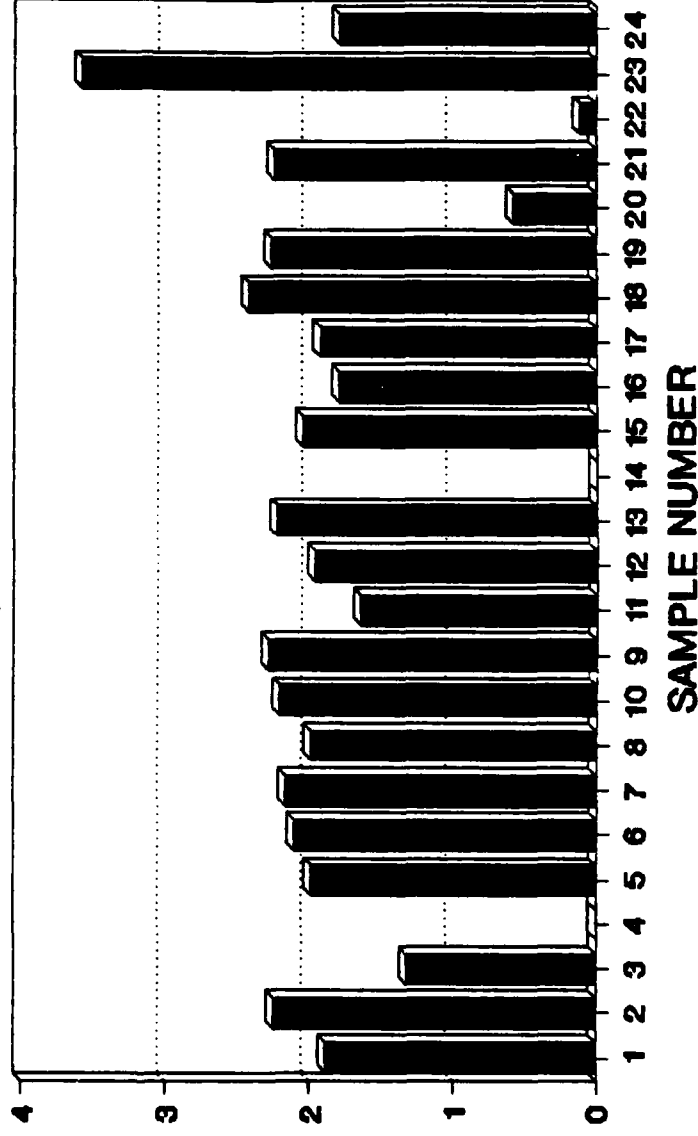
# HSSA RECIPROCATING WEAR TESTS 50 N LOAD, IN AIR, 1.76 GPa (MAX)



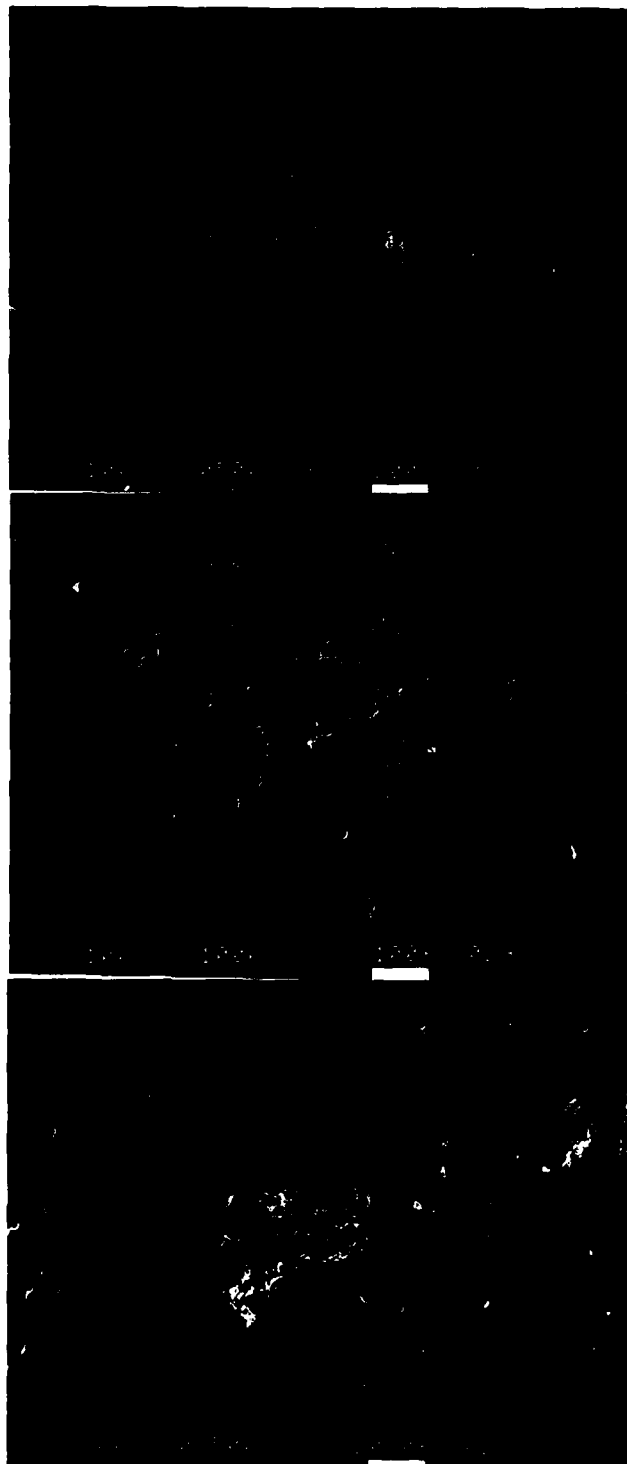
NATIONAL CENTRE OF TRIBOLOGY

# **HSSA RECIPROCATING WEAR TESTS** **50 N LOAD, IN AIR, 1.76 GPa (MAX)**

WEAR RATE ( $\text{m}^3/\text{m}^2 \times 10^{-13}$ )

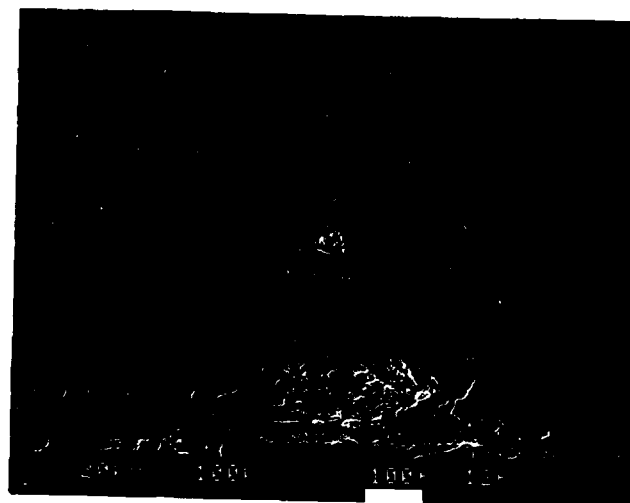


NATIONAL CENTRE OF TRIBOLOGY



Back-scattered  
Image

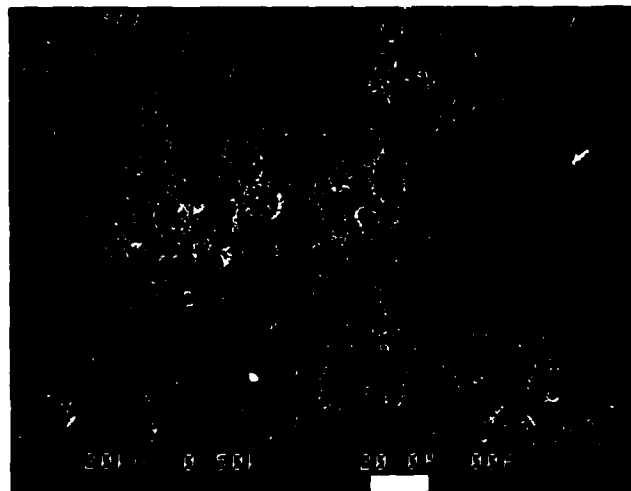
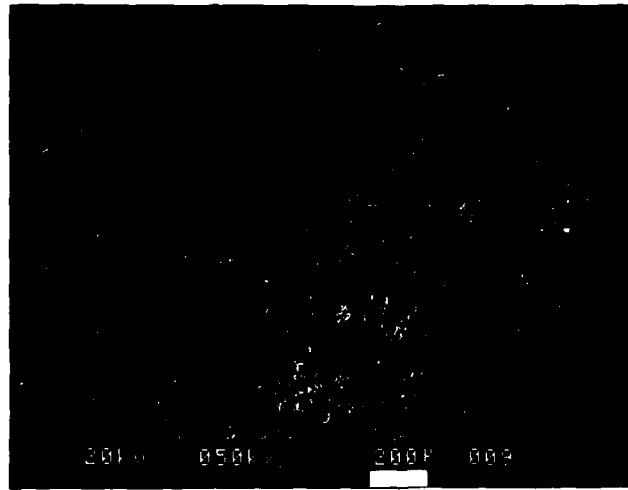
Figure 8: HSSA4, 10kV Accelerating Voltage, Showing Metal Transfer.



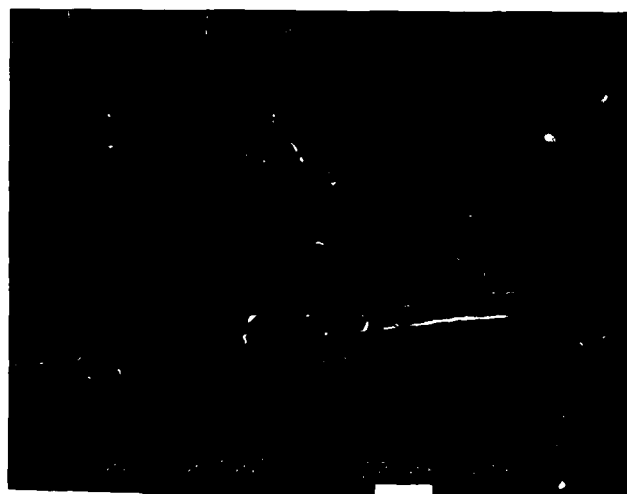
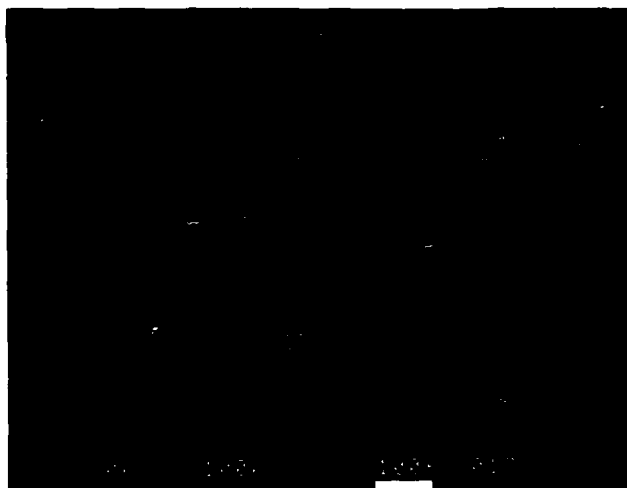
Back Scattered Image

Figure 9:  
HSSA 22, 50N. Hole in Coating in Scar.

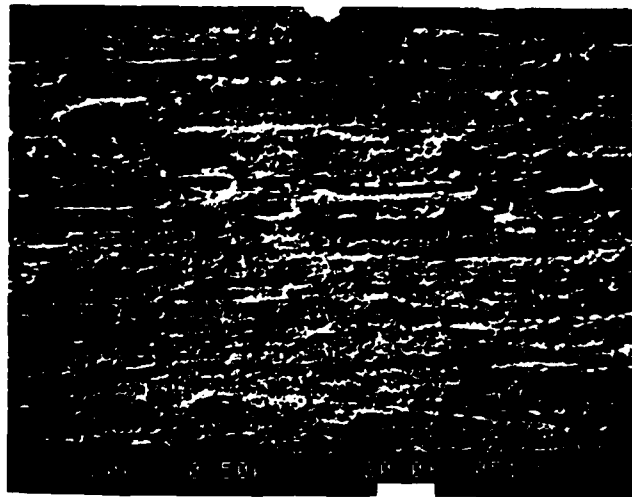
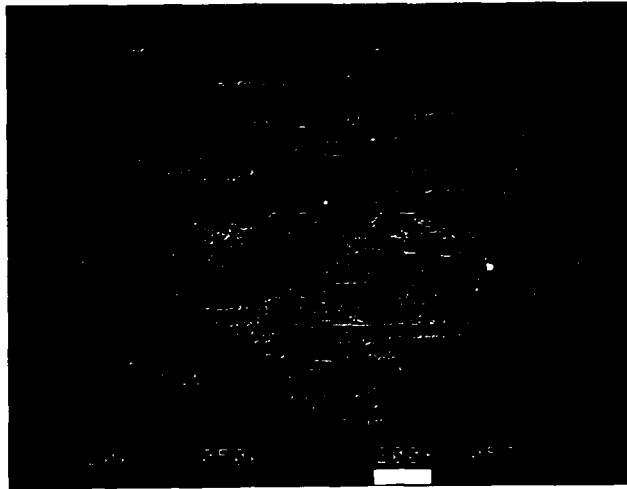
**APPENDIX 1: Scanning Electron Micrographs**



HSSA1: Solution Heat Treated

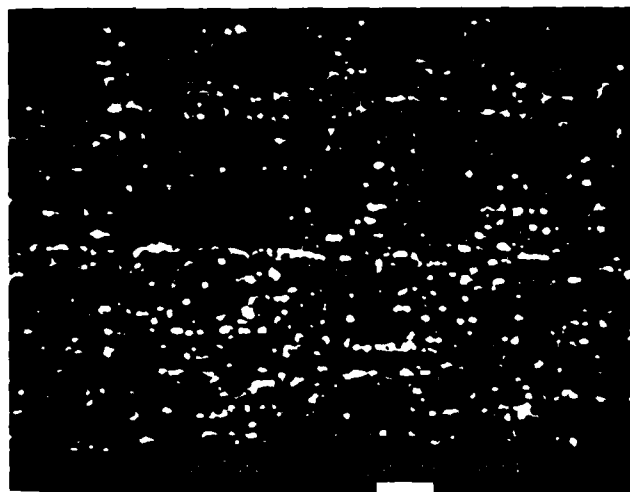


HSSA 2: Hardened and Ground

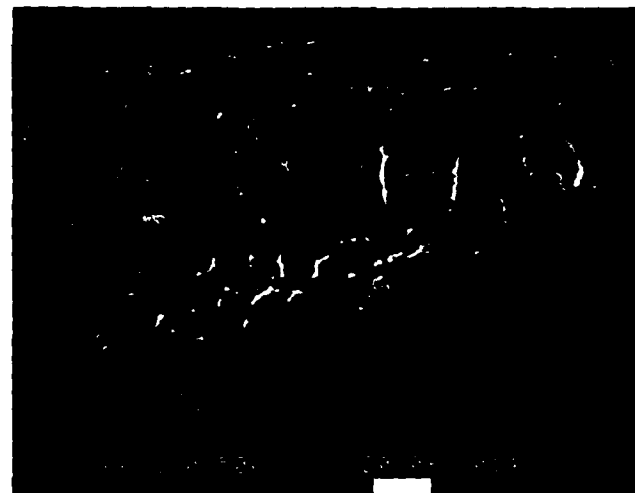
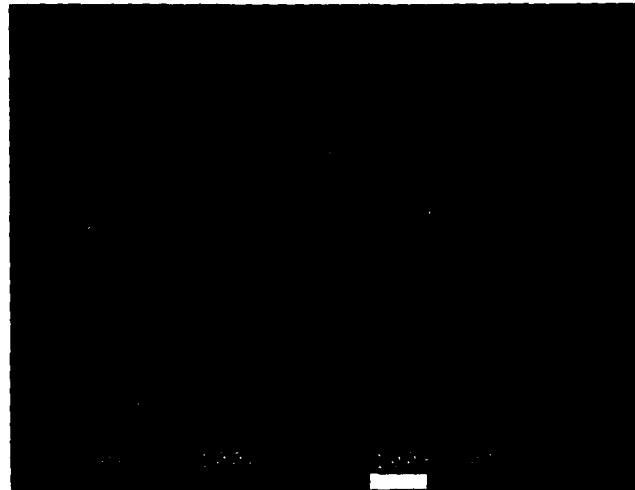


HSSA 7: Hard Anodised 1

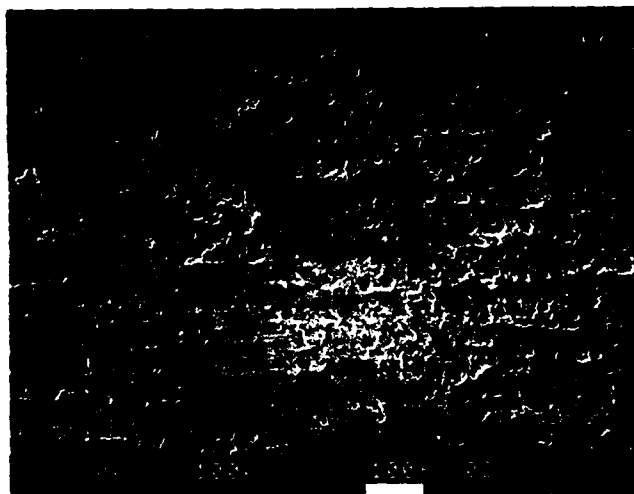




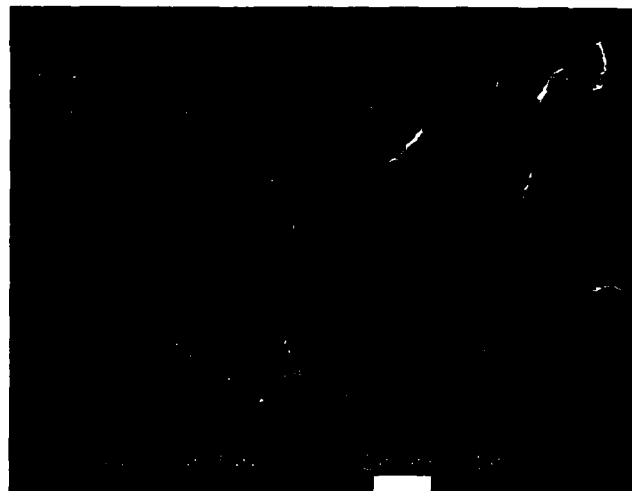
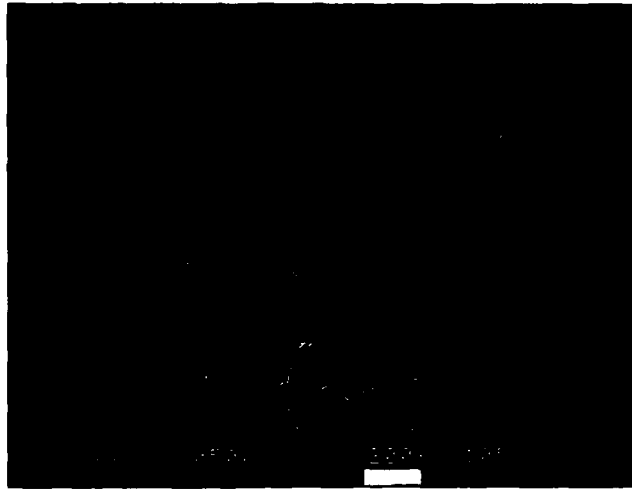
HSSA 11: Hard Anodised 4



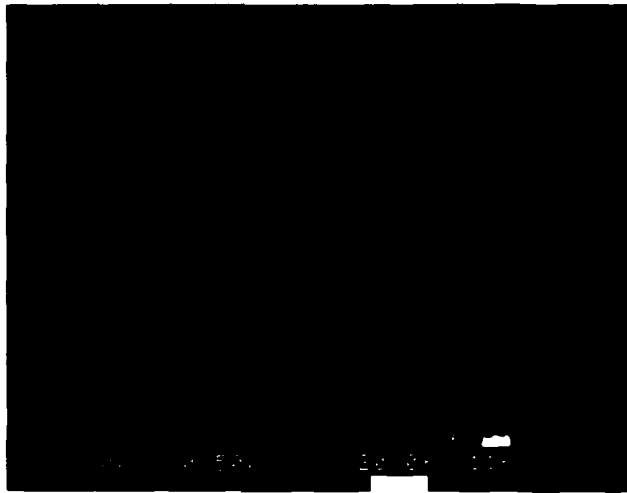
HSSA13: Plasma Nitrided 2



HSSA15: Nitrosc 1



HSSA 19: Pack Aluminising 2



HSSA21: Diamond-like Carbon



HSSA23: TiN/HfN Multilayer

**APPENDIX 2: Optical Micrographs**

ISSA  
Samples  
1, 2 & 3

HSSA1

1200



6362

HSSA2

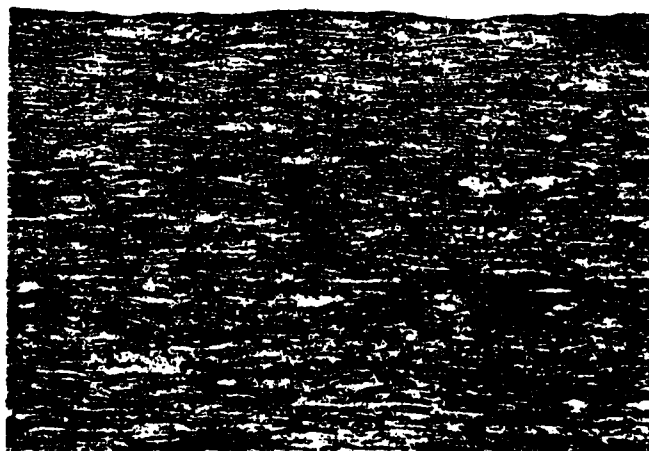
1200



6363

HSSA3

1200

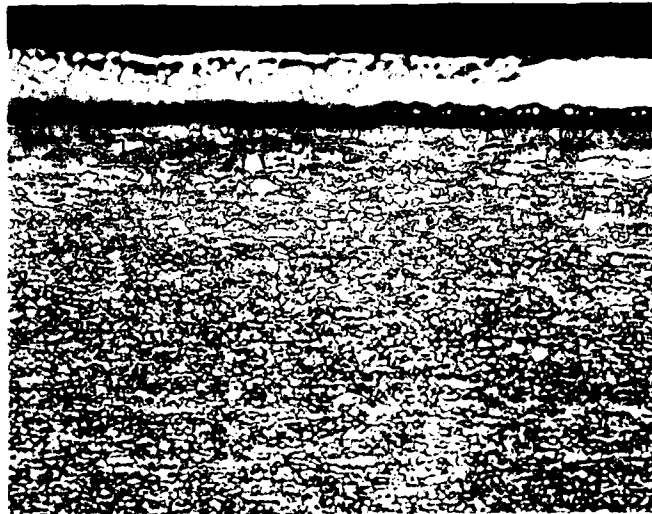


6364

SSA  
amples  
485

455A 4

1200



6365

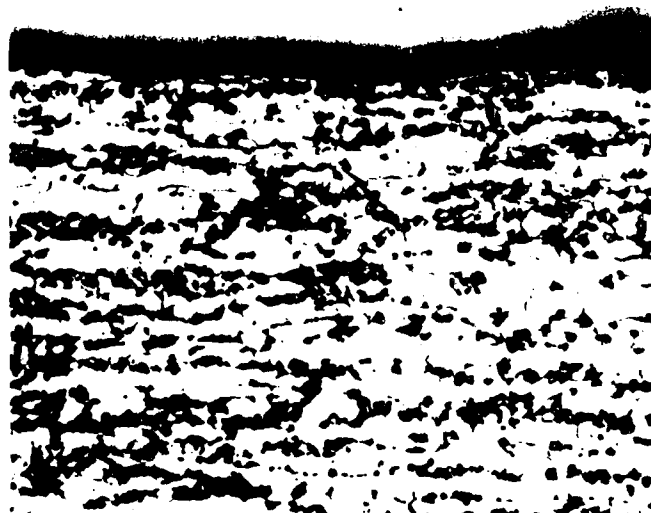
455A 5

1200



455A 5

1300



6367



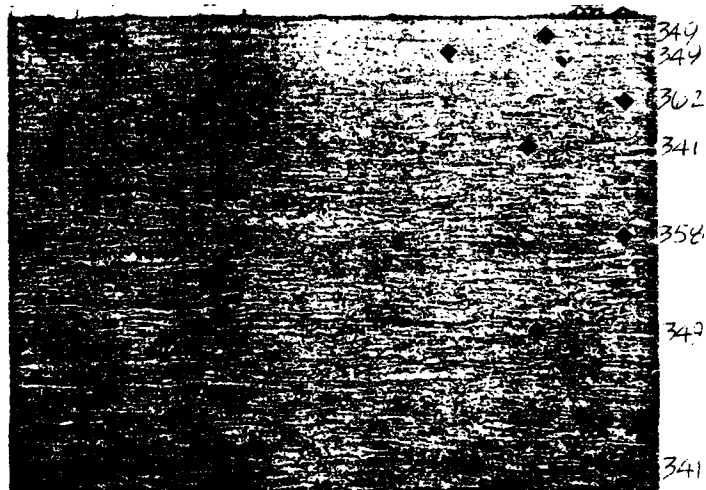
ISSA 6

HSSA6 side(b) X200



5451

Hardened + Ion Implanted  
HSSA6 side(a) X200

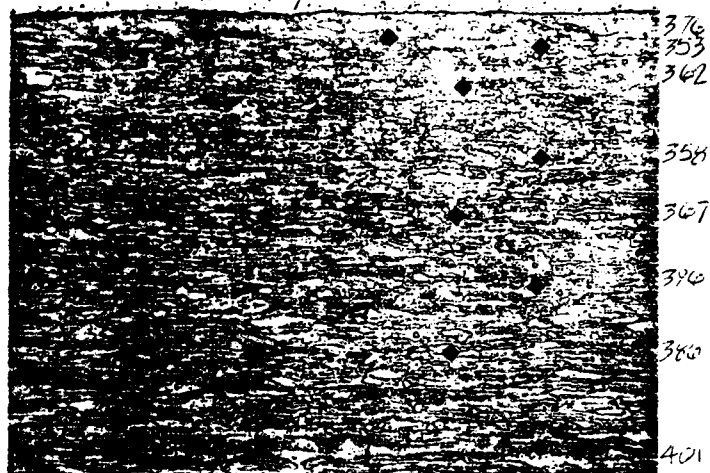


5450

bulk = 391 HV (50g)

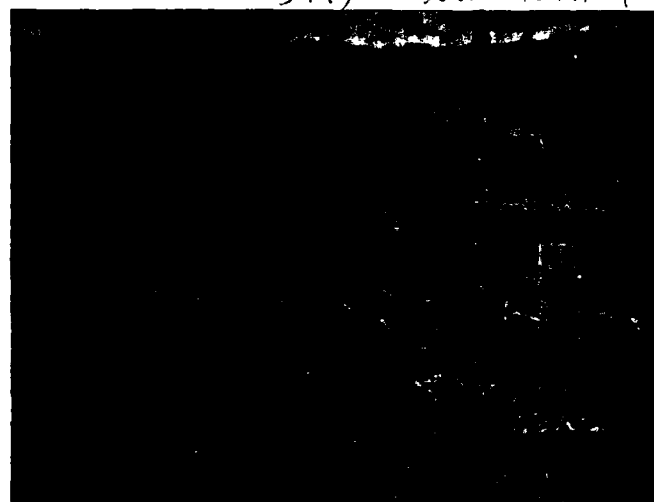
HSSA7

Soln Treated  
HSSA7 Petron Anodised X200



5449 bulk = 401 HV (50g)

HSSA7



X1000

5448

S.T.  
HSSA7 Centre X1000

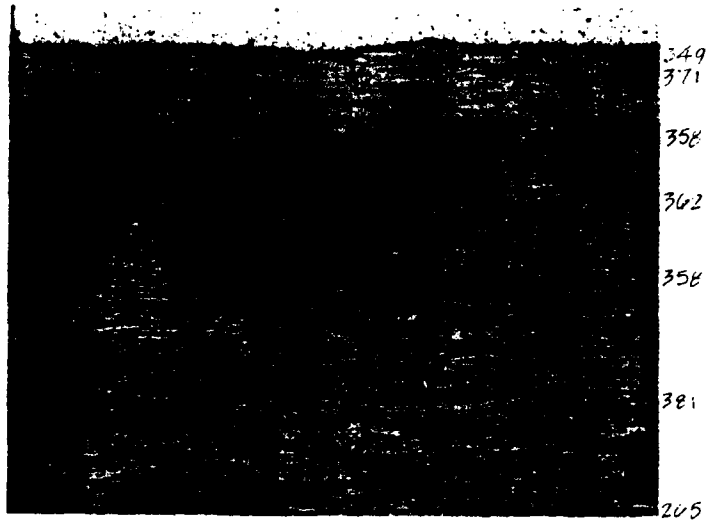


5447

HSSA 8

1

HSSA 8 Hardened  
Ground  
Pecton Anodised  
X 200



549  
371  
358  
362  
358  
381  
205

5446 bulk = 412 HV (50g)

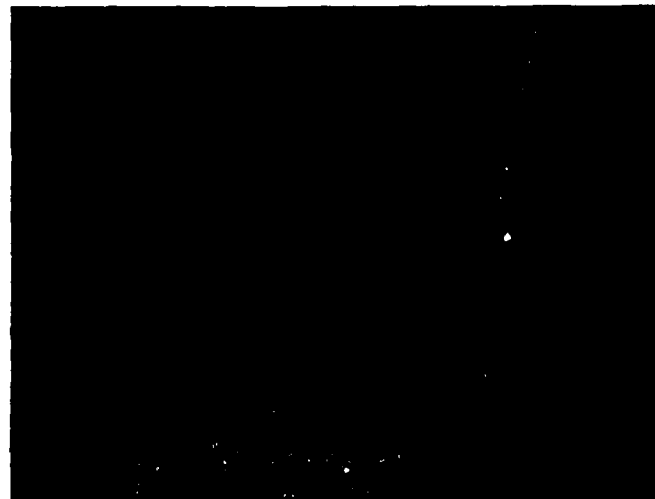
HSSA 8

X1000



5445

HSSA 8<sup>H</sup> Centre  
X1000



5444

X

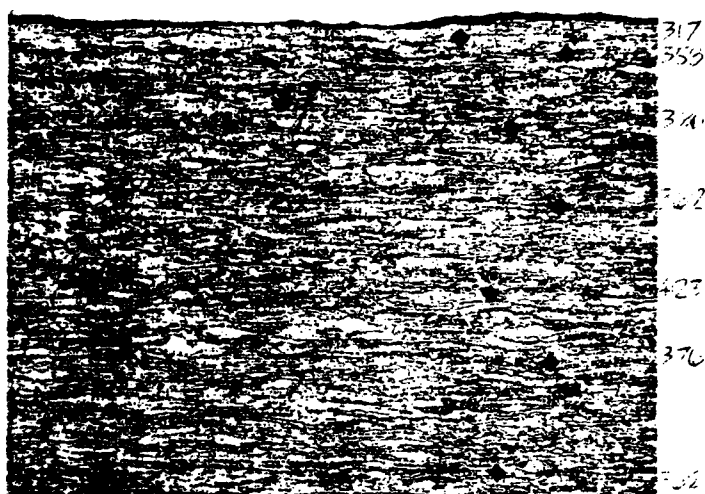
[ISSA 9

ISSA 9

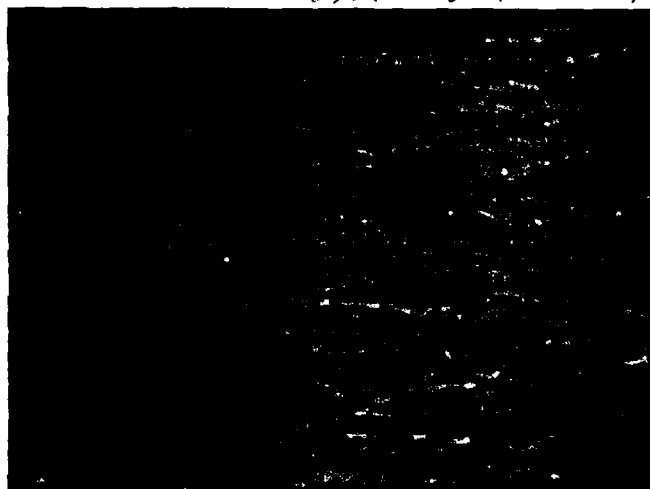
X200

ISSA 9

X1000



bulk = 353114 5459



5450

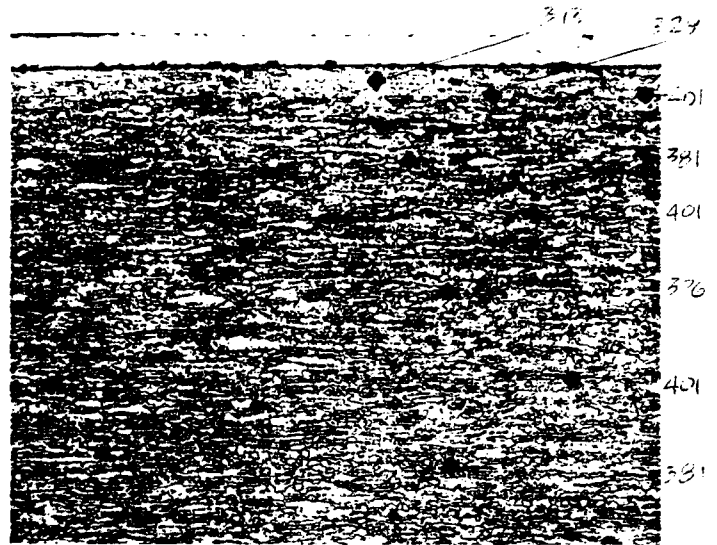
185A11

185A11

X200

185A11

X1000



bulk = 40.7HV 5453



5452

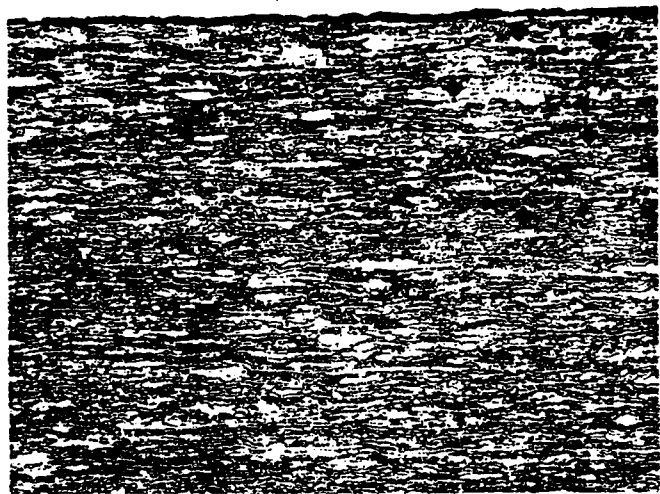
HSSA12

HSSA12

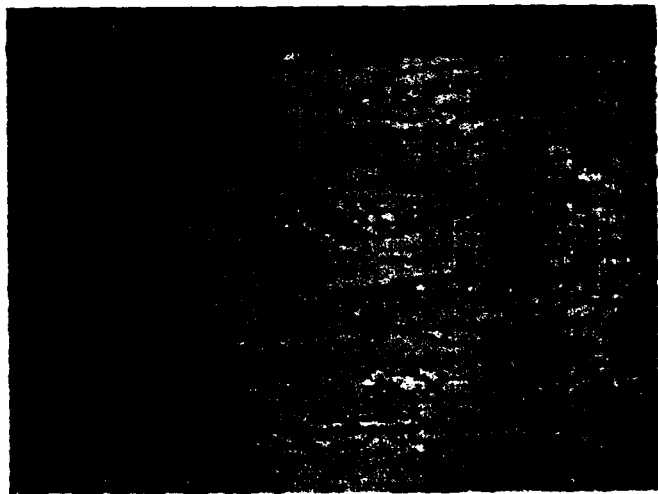
X200

HSSA12

X1000



Wicks 401 HV 5457



5456

225  
252  
552  
381

2.2

\*

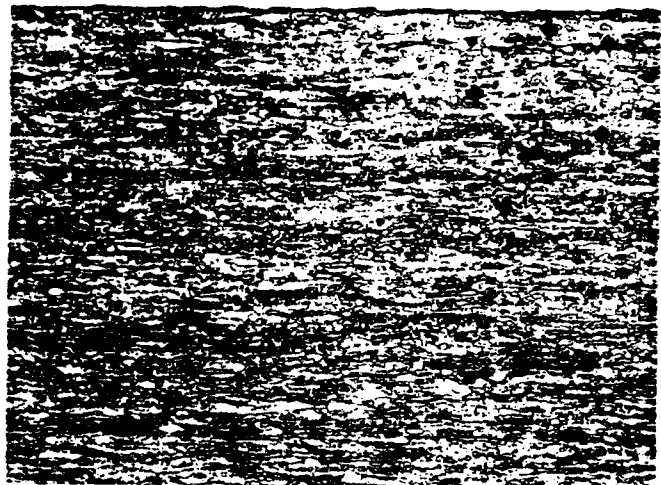
I 155A 13

HSSA13

X200

HSSA13

Centre X1000



bulk = 107 HV 5455



5454

SSA14

353

(50g/15sec)



353

341

329

311

X200

SSA14

BULK  
MACRO(20kg)=356HV

mk ↓ 341HV 5700

SSA15

384

386

386

(50g/15sec) 5699



396

386

X200

SSA15

mk ↓ 401HV

BULK  
MACRO(20kg)=388HV



HSSA 16

5705



X50

HSSA 16

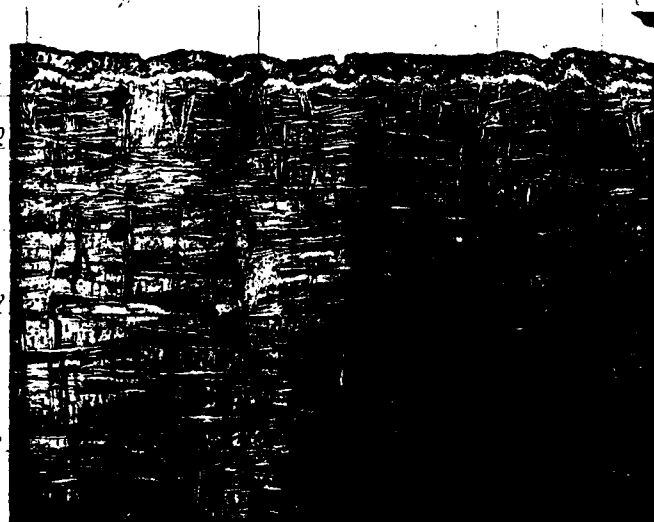
260

243

321 50g/15522 358

357

207 (259/522)



X200

5701

HSSA 16

214

262

271

280

283

Rock 280 HV  
293

Rock 207 (2014) = 313 HV  
281

HSSA 16

5703

HSSA 16

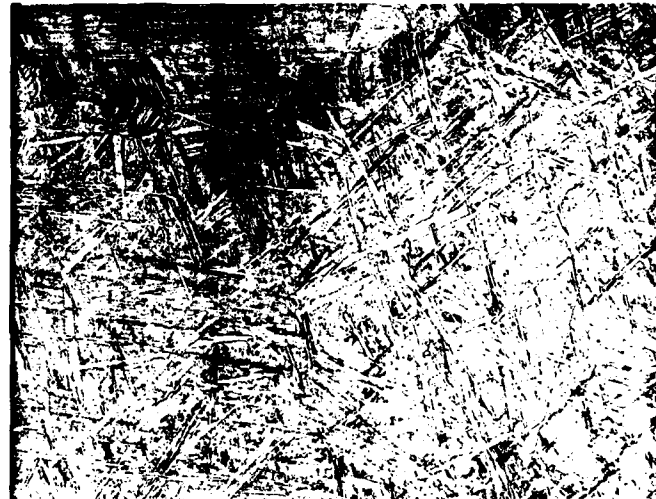


45mm

X1000

5704

HSSA 16



X200

5702

HSSA 16

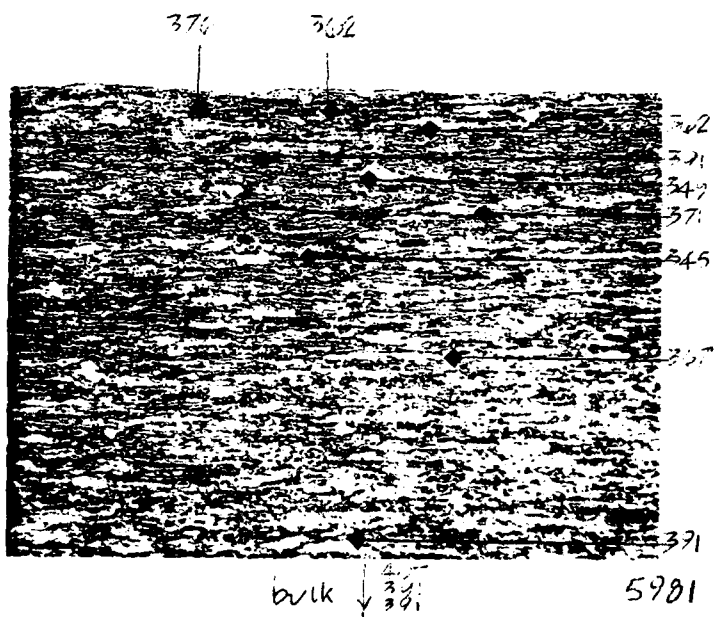


X1000

HSSA17

HSSA17

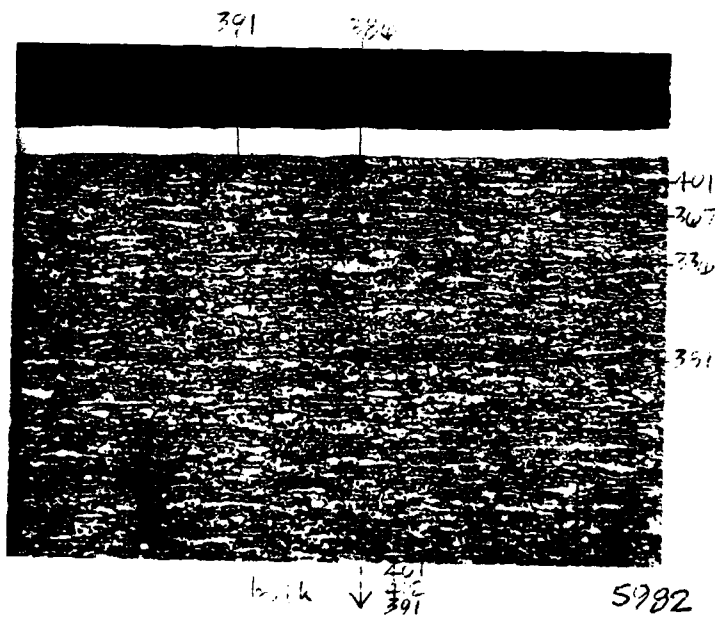
X200



HSSA18

HSSA18

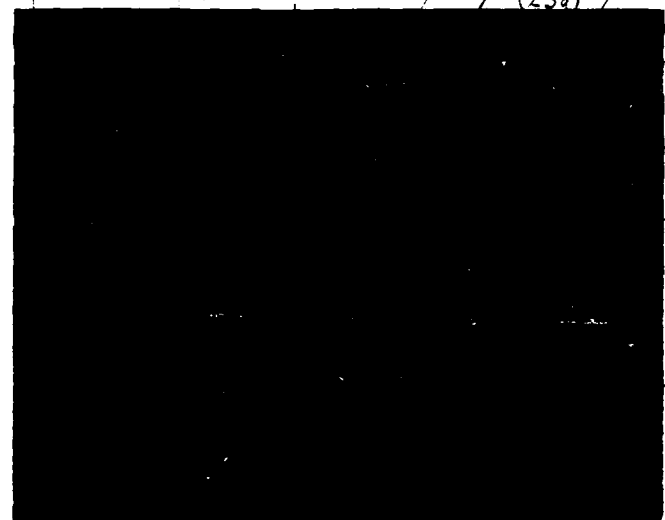
X200



ISSA 19

349 401 307 209 211 (25a) 310

ISSA 19



251  
273  
313  
297  
310  
358  
306

X200

bulk ↓ 283  
312  
325

5983

ISSA 19



X200

5984

HSSA 19

HSSA19

X1000



5985

HSSA19

X1000

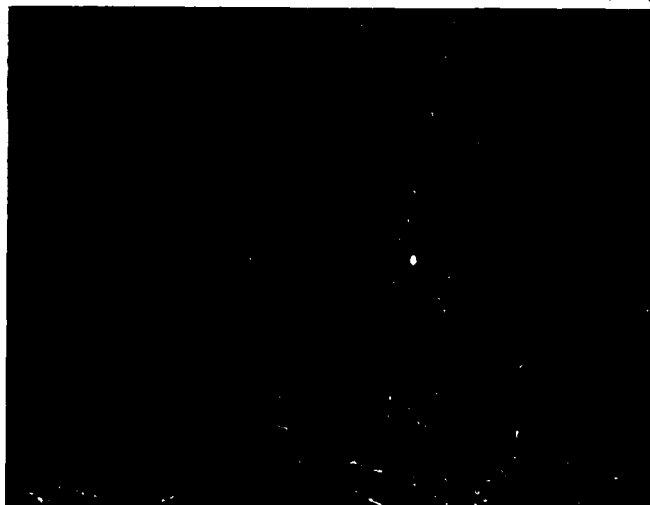


5986

HSSA

bulk

X1000



5987

BULK

SSA 20

(carb/Carbo  
Nitrated  
tuyton)

HS5A 20

N100

HS5A20

N100

0  
0.1  
0.2  
0.3  
0.4  
0.5  
(mm)



HSSA 21

Hard  
Carbon

HSSA 21

X200

371

3/10



349

386

307

↓ BULK

6060

X1000



HSSA 21

6059

HSSA 22

Special  
TIN

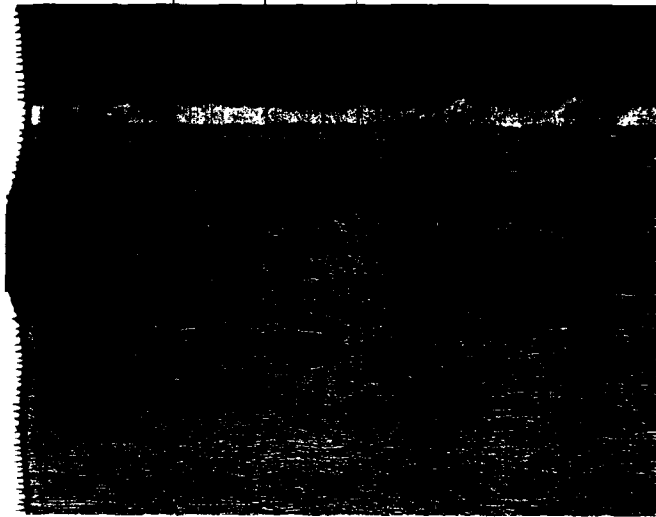
HSSA 22

X200

HSSA 22

X1000

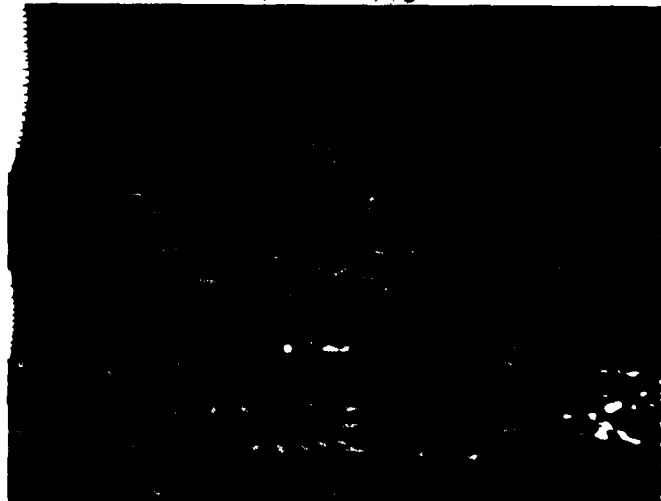
407 412 357



387

↓ bulk 401  
326

6058



3  
300

6057



ISSA 23  
 IN/HfN  
 2x1µm  
 layers'

ISSA23

X200

ISSA23

X1000

ISSA23

X1000

317 386



358  
 362  
 346

↓ bulk 336  
 346  
 381

6054



2µm

6055



5µm

6056

between the 2 sides of the sample

SSA 24

luminised  
PAL 85

SSA 24

x200

SSA 24

x200

SSA 24

x200

gap caused  
by  
fault  
in matrix

516 514 512 HV at 50g

321  
313  
313  
303

50µm

61200

6179

6178

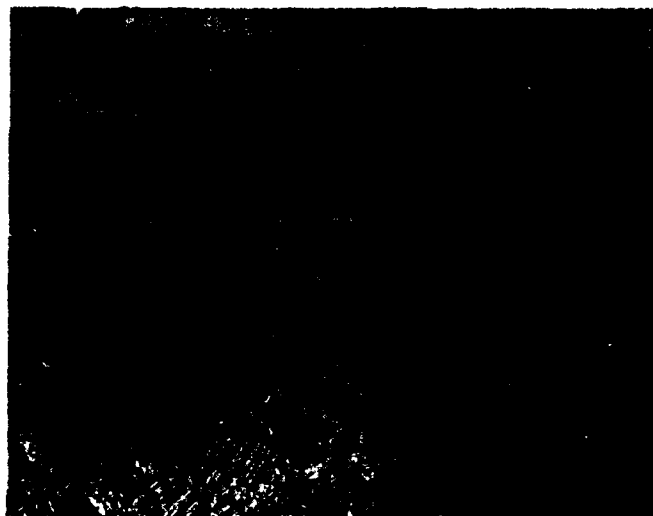
ISSA 24

Luminised

PAL 85

ISSA 24

X1000



6201

ISSA 24

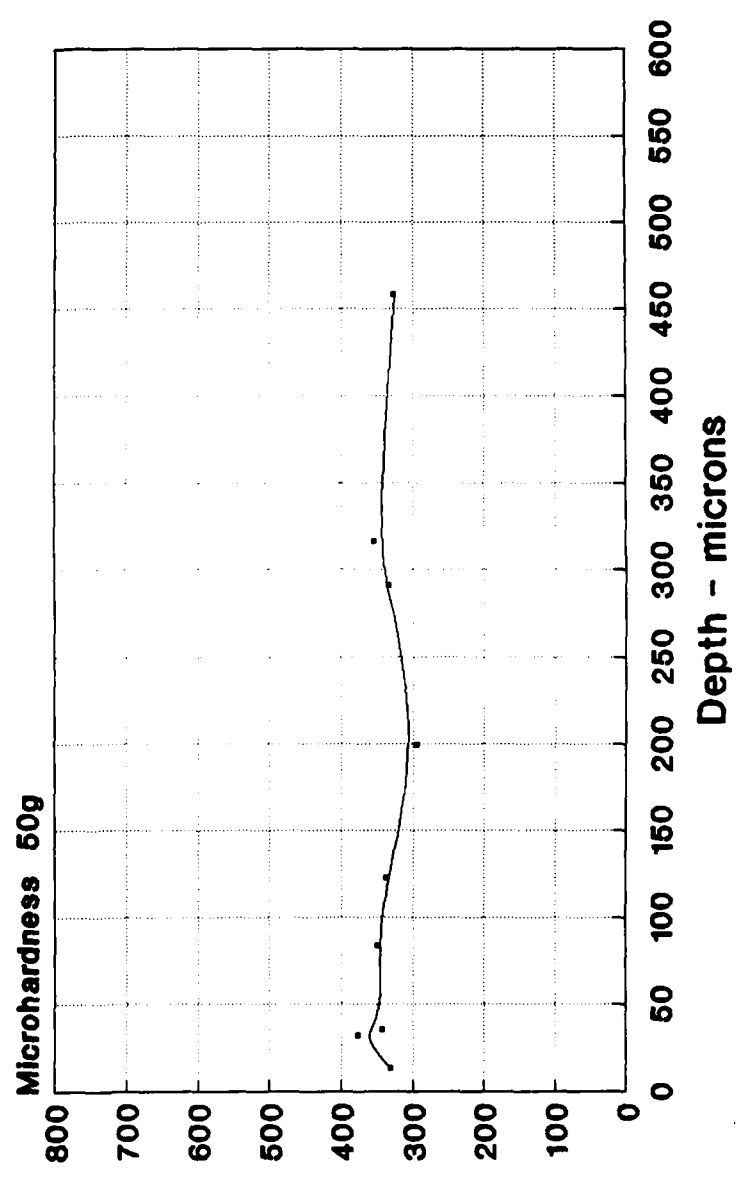
X1000



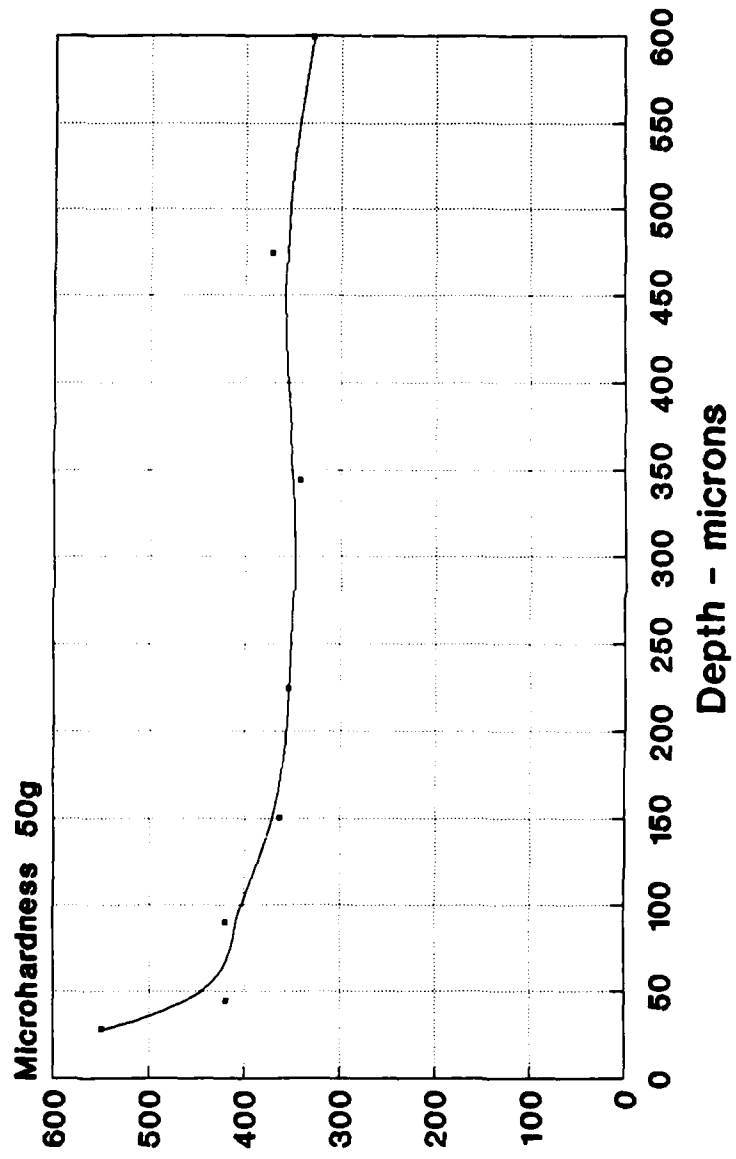
6197

**APPENDIX 3: Microhardness Depth Profiles**

# MICROHARDNESS DEPTH PROFILE HSSA 3/ PLASMA NITROCARBURIZED #1

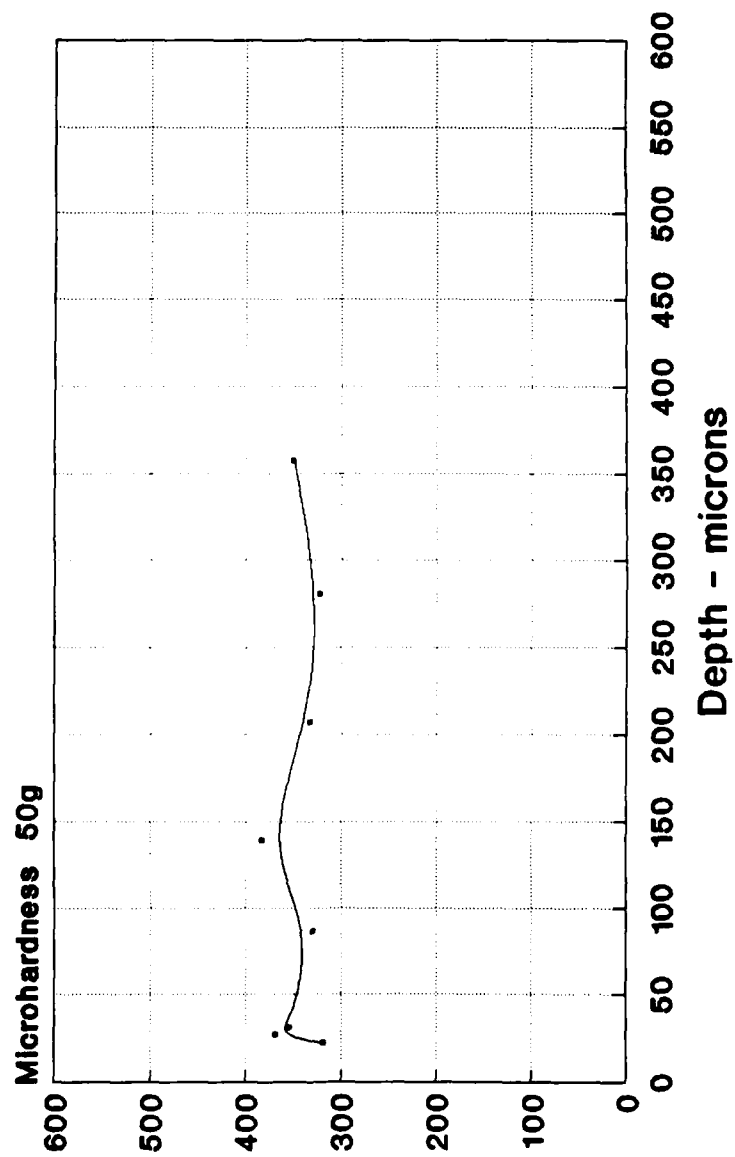


# MICROHARDNESS DEPTH PROFILE HSSA 4/ BETA NITROCARBURIZED #1



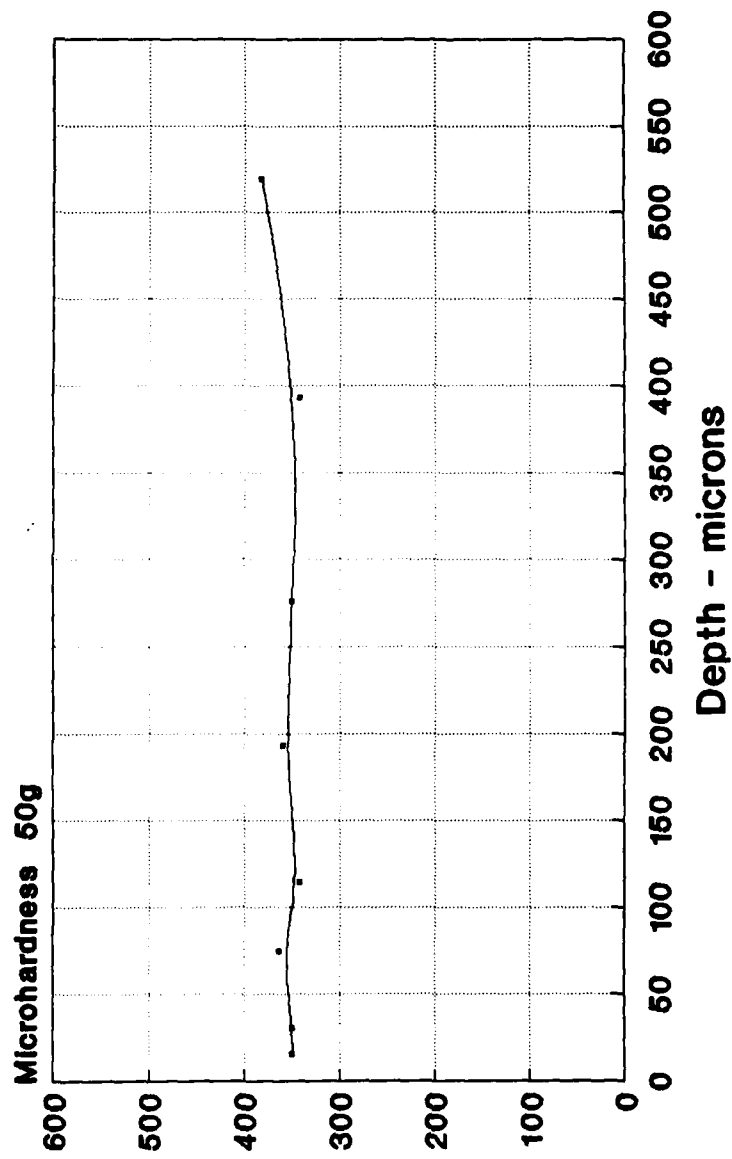
NATIONAL CENTRE OF TRIBOLOGY

# MICROHARDNESS DEPTH PROFILE HSSA 5/ ION IMPLANTATION #1



NATIONAL CENTRE OF TRIBOLOGY

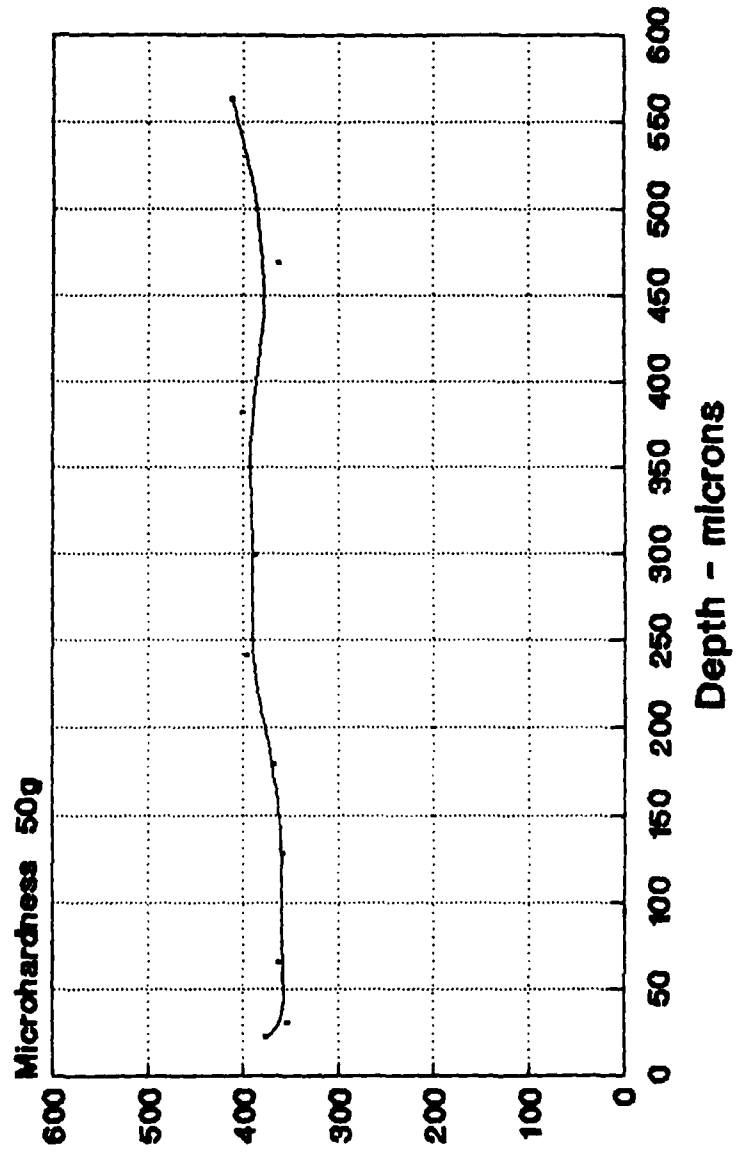
# MICROHARDNESS DEPTH PROFILE HSSA 6/ ION IMPLANTATION #2



NATIONAL CENTRE OF TRIBOLOGY

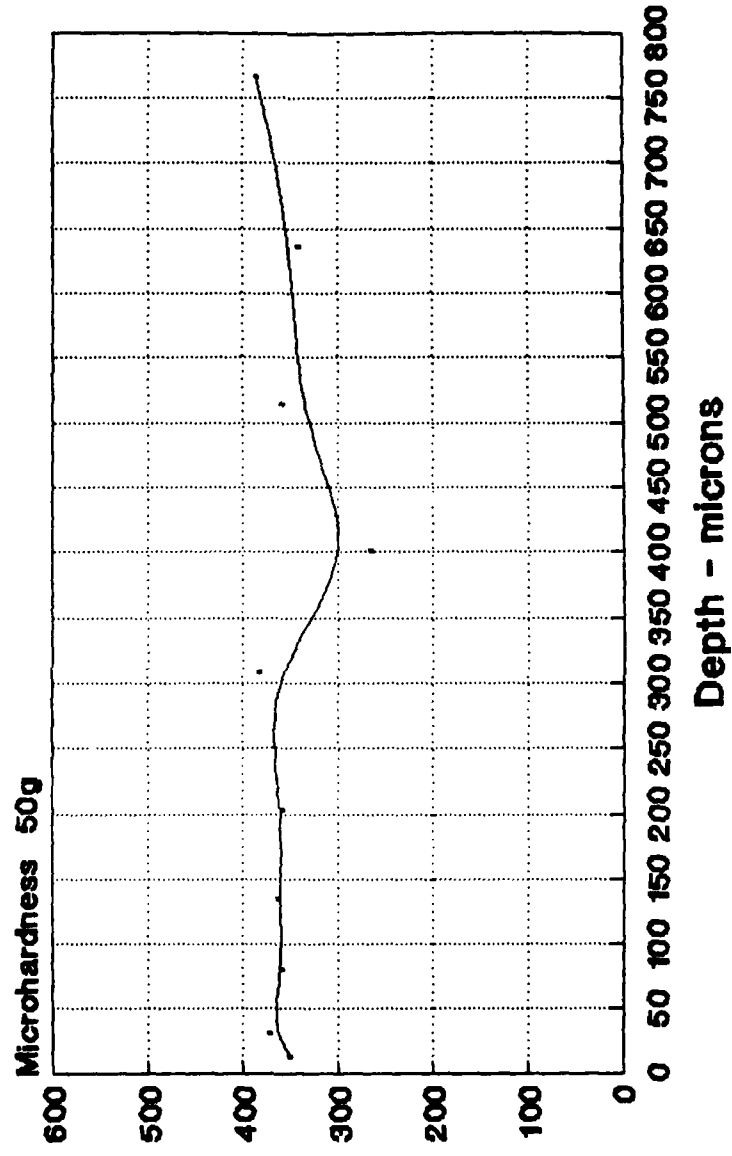


# **MICROHARDNESS DEPTH PROFILE** **HSSA 7/ HARD ANODISED #1**



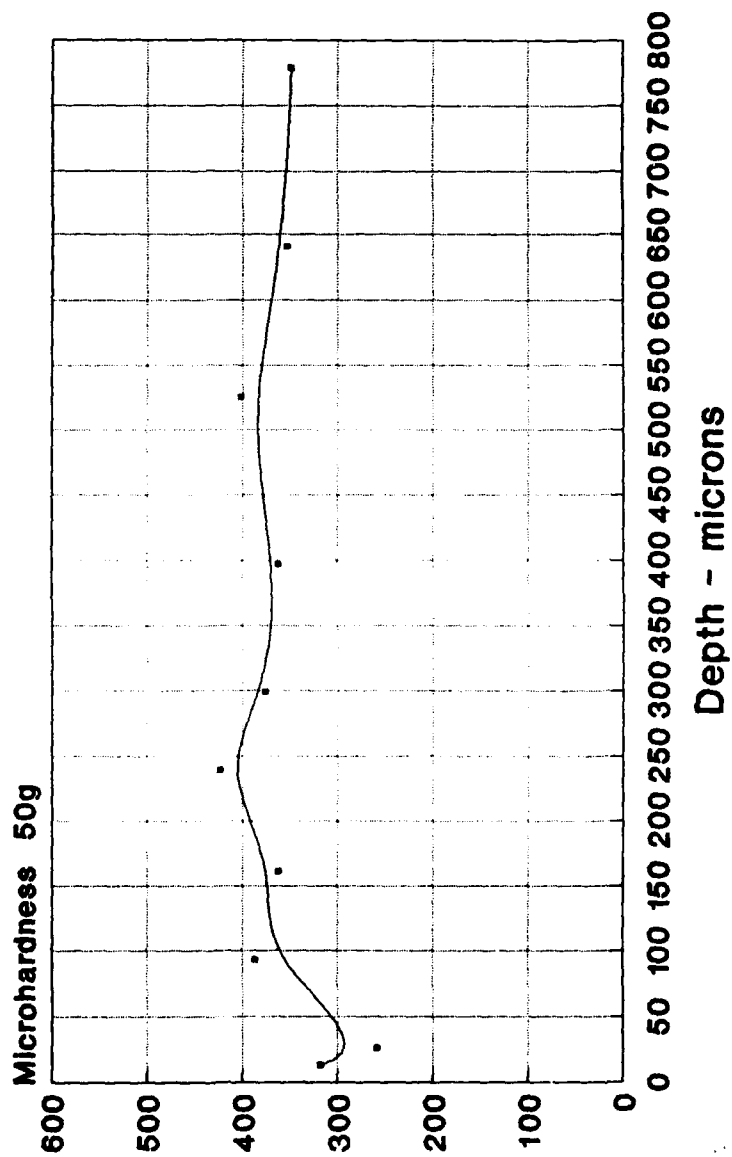
NATIONAL CENTRE OF TRIBOLOGY

# MICROHARDNESS DEPTH PROFILE HSSA 8/ HARD ANODISED #2



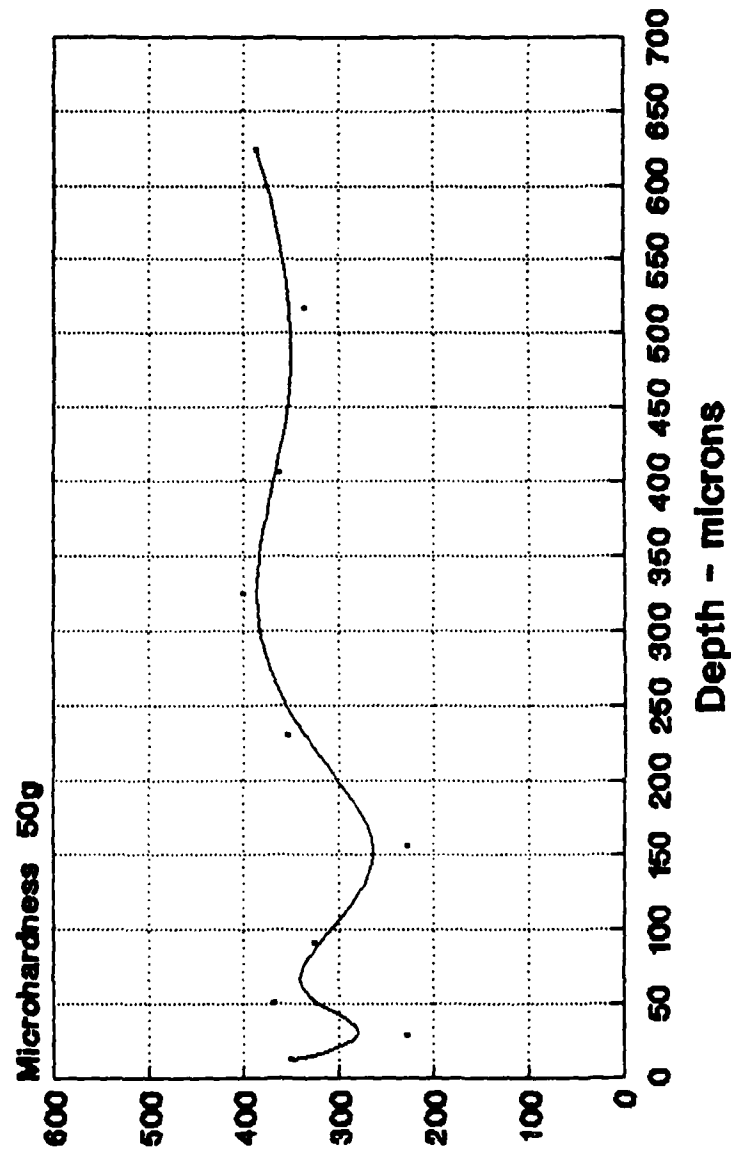
NATIONAL CENTRE OF TRIBOLOGY

# MICROHARDNESS DEPTH PROFILE HSSA 9/ PLASMA NITROCARBURIZED #1



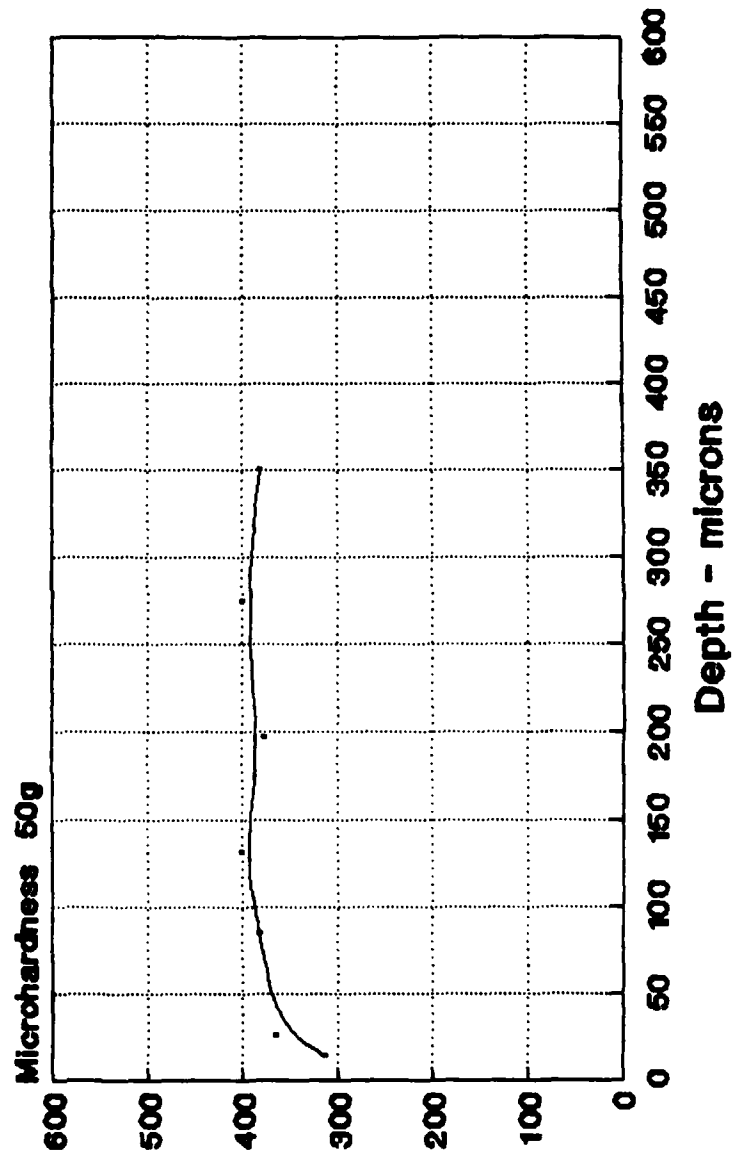
NATIONAL CENTRE OF TRIBOLOGY

# MICROHARDNESS DEPTH PROFILE HSSA 10/ HARD ANODISED #3



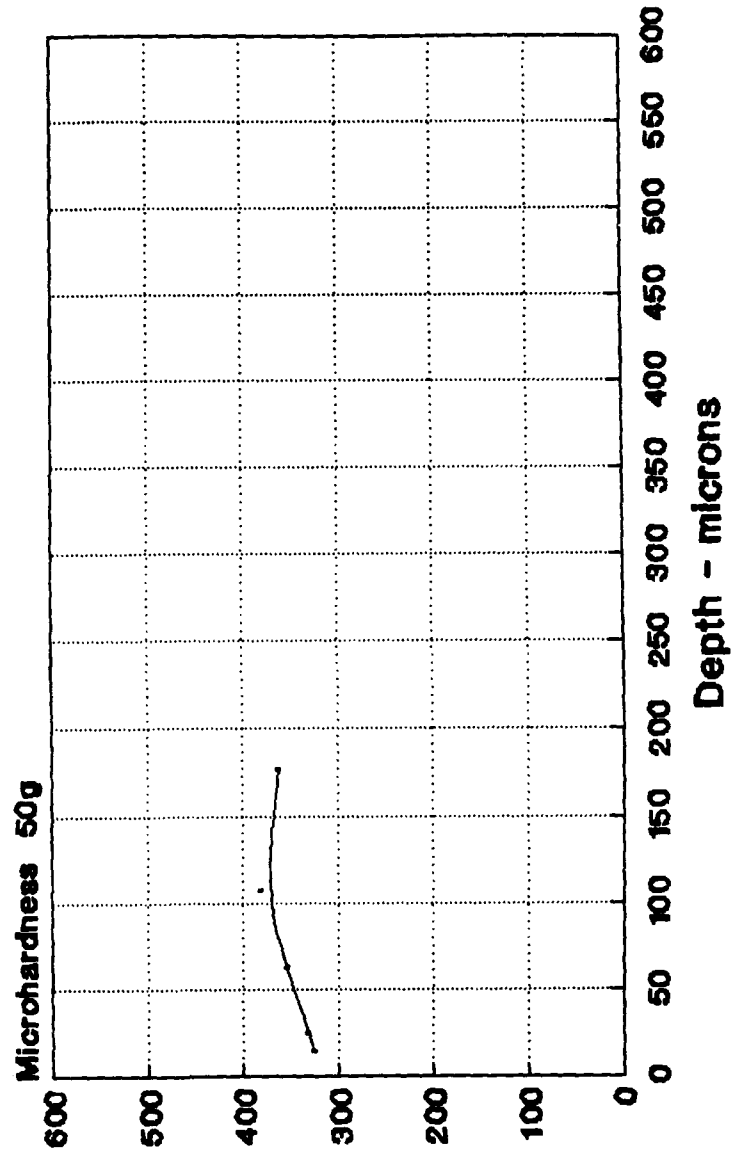
NATIONAL CENTRE OF TRIBOLOGY

# MICROHARDNESS DEPTH PROFILE HSSA 11/ HARD ANODISED #4



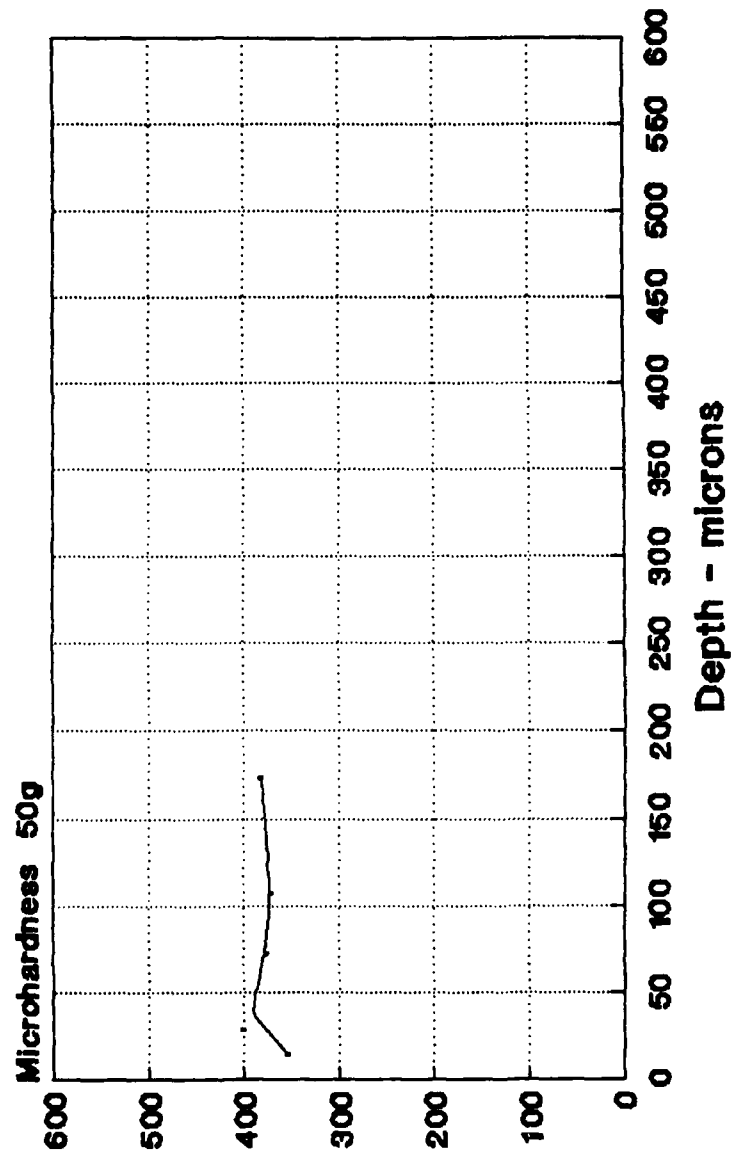
NATIONAL CENTRE OF TRIBOLOGY

**MICROHARDNESS DEPTH PROFILE  
HSSA 12/ PLASMA NITRIDED #1**



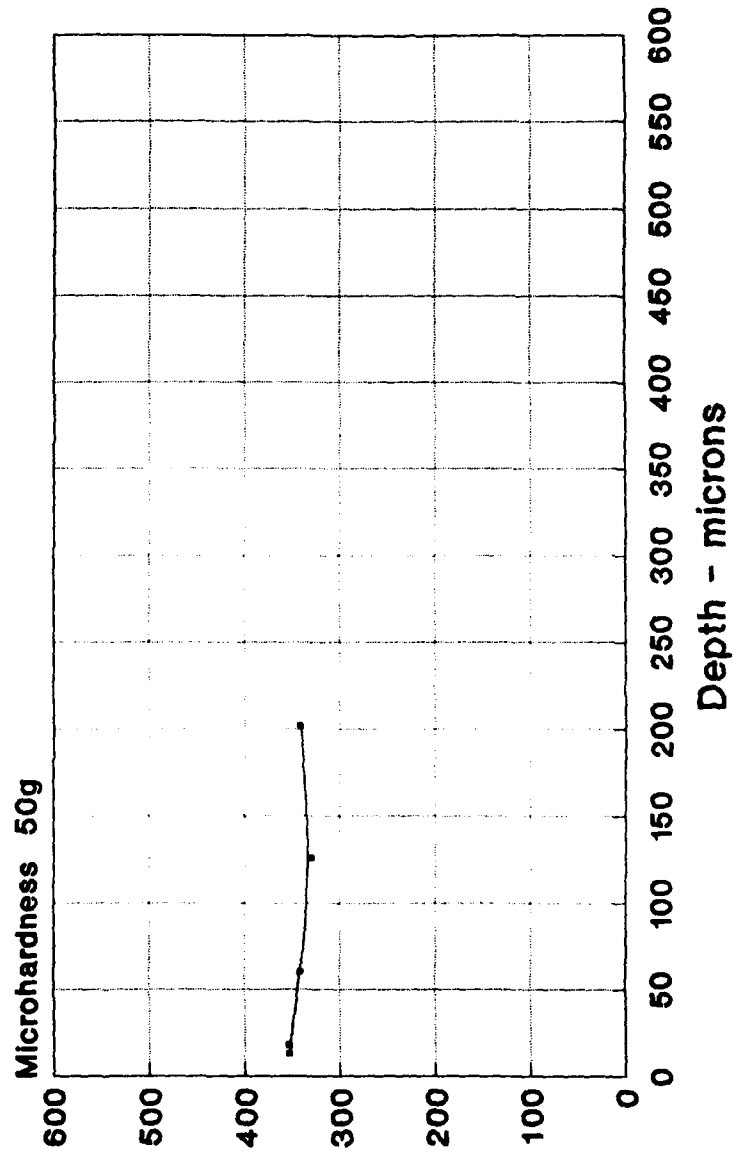
NATIONAL CENTRE OF TRIBOLOGY

# **MICROHARDNESS DEPTH PROFILE** **HSSA 13/ PLASMA NITRIDED #2**



NATIONAL CENTRE OF TRIBOLOGY

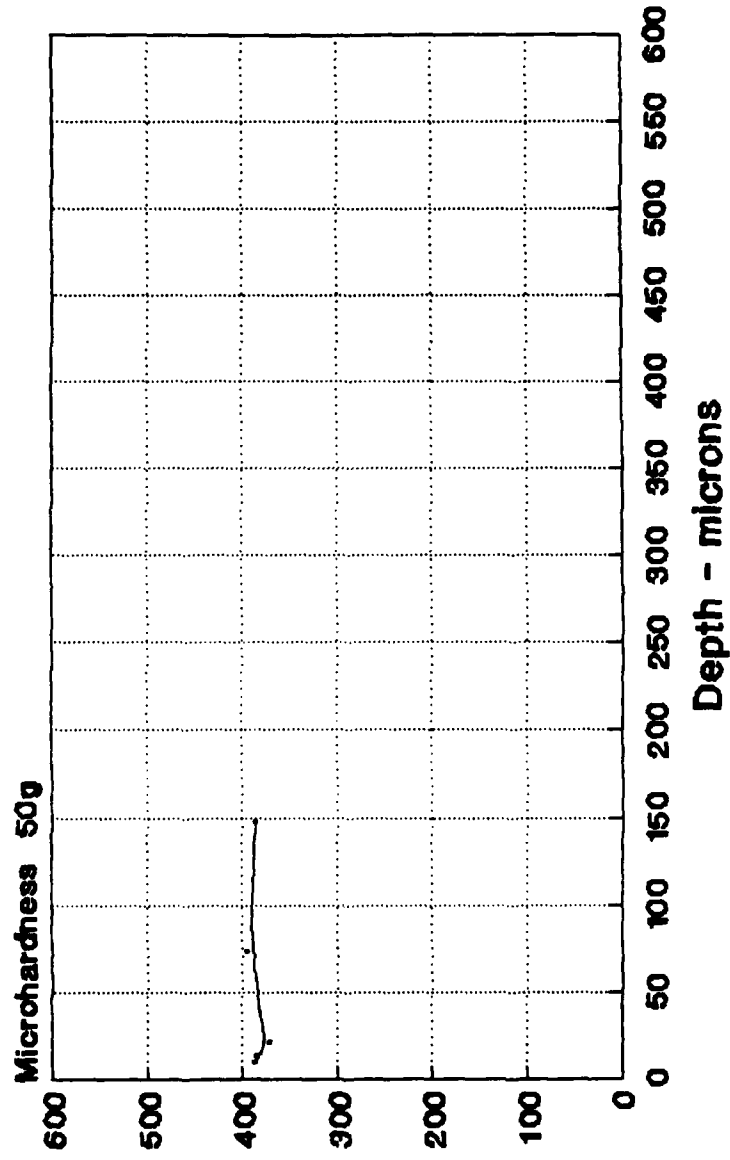
# MICROHARDNESS DEPTH PROFILE HSSA 14/ HT NITROCARBURIZING #1



NATIONAL CENTRE OF TRIBOLOGY

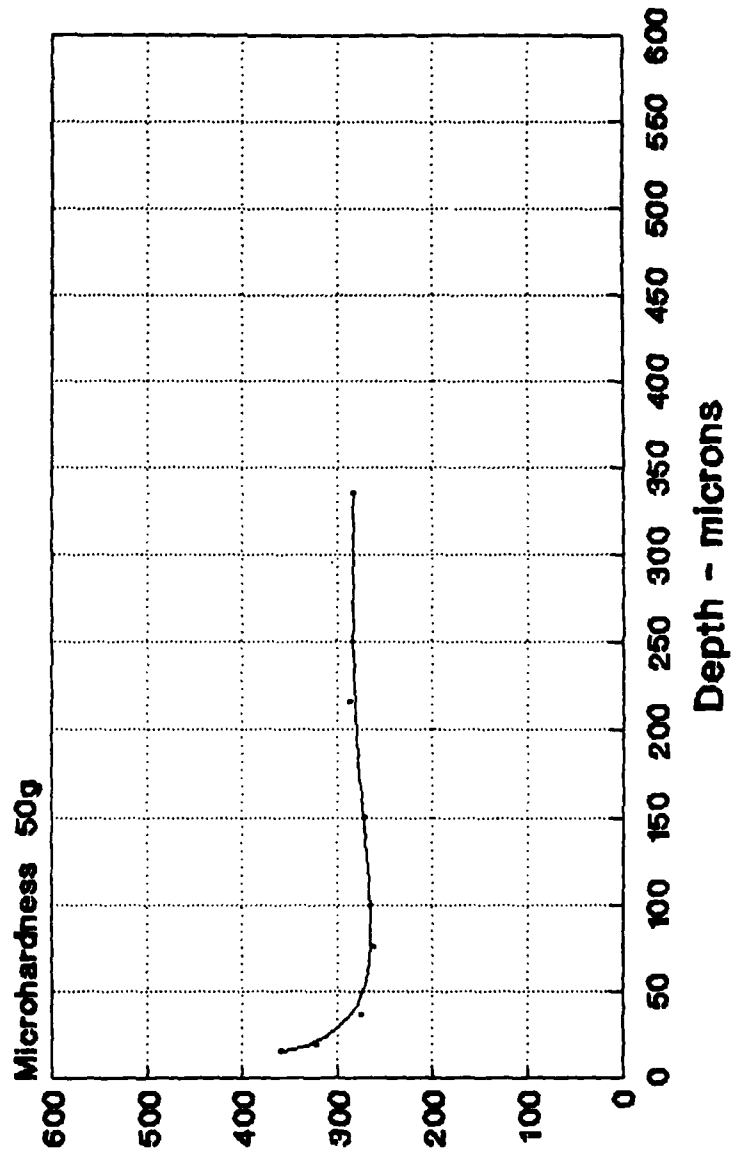


# MICROHARDNESS DEPTH PROFILE HSSA 15/ NITROX #1



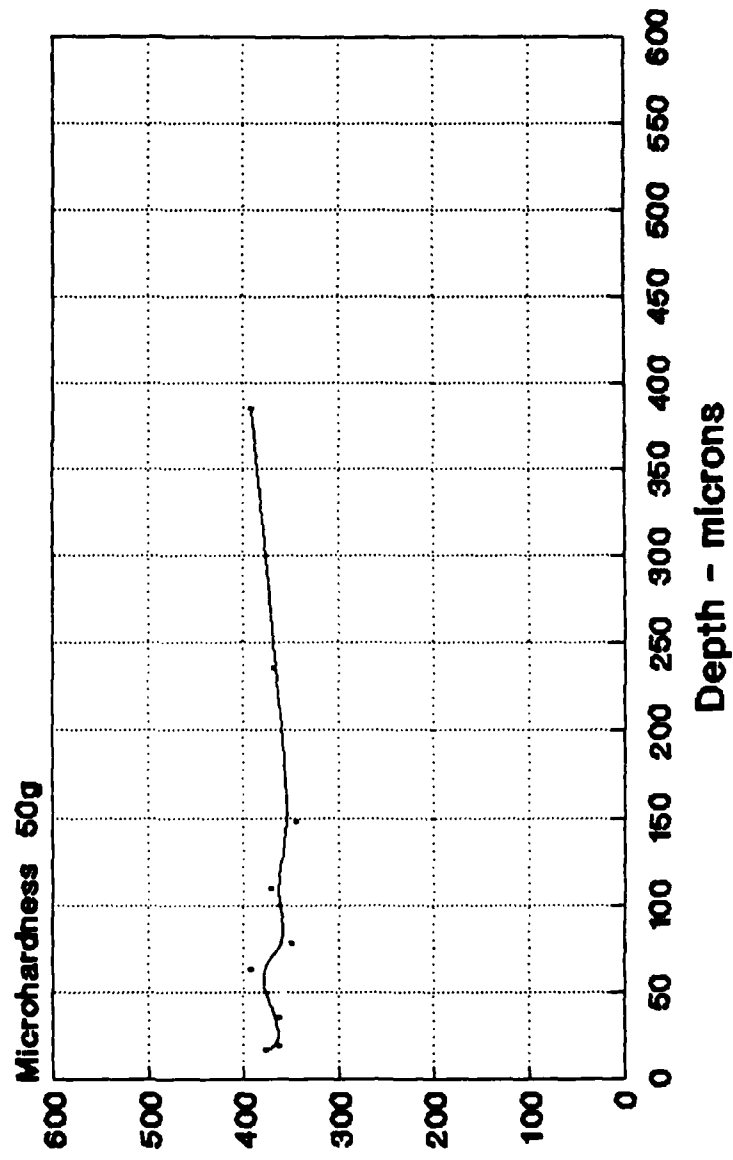
NATIONAL CENTRE OF TRIBOLOGY

# MICROHARDNESS DEPTH PROFILE HSSA 16/ PACK ALUMINISING #1



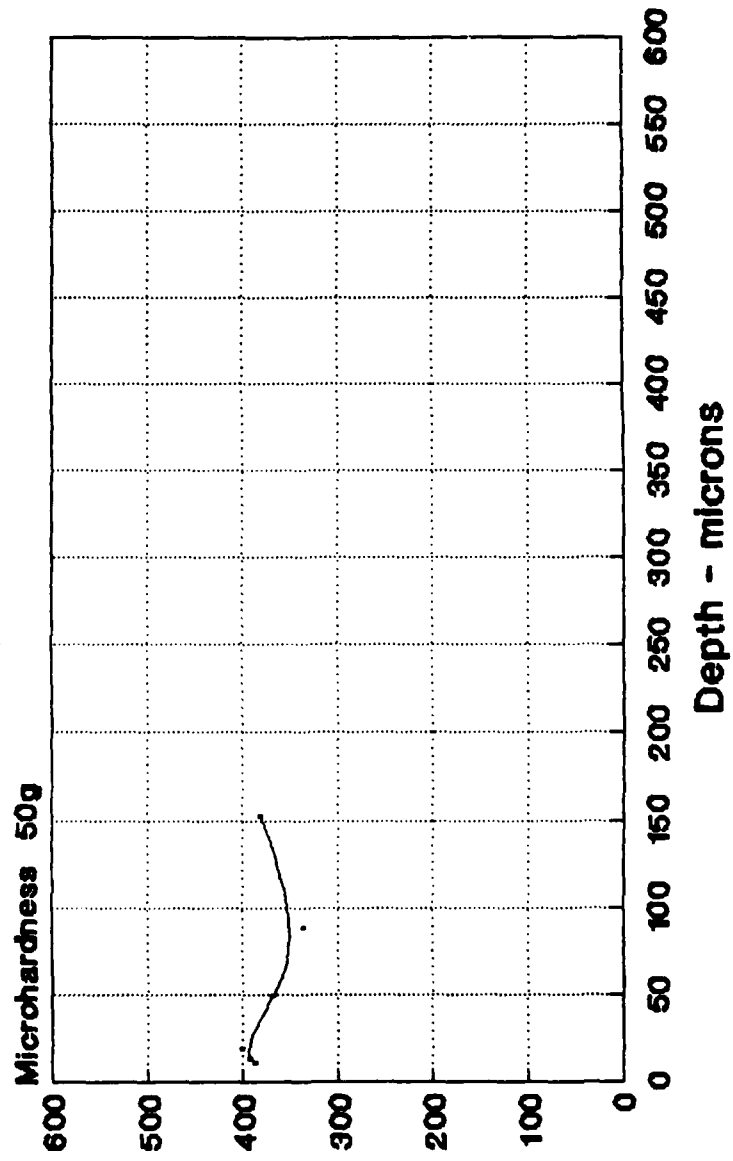
NATIONAL CENTRE OF TRIBOLOGY

# MICROHARDNESS DEPTH PROFILE HSSA 17/ NITROX #2

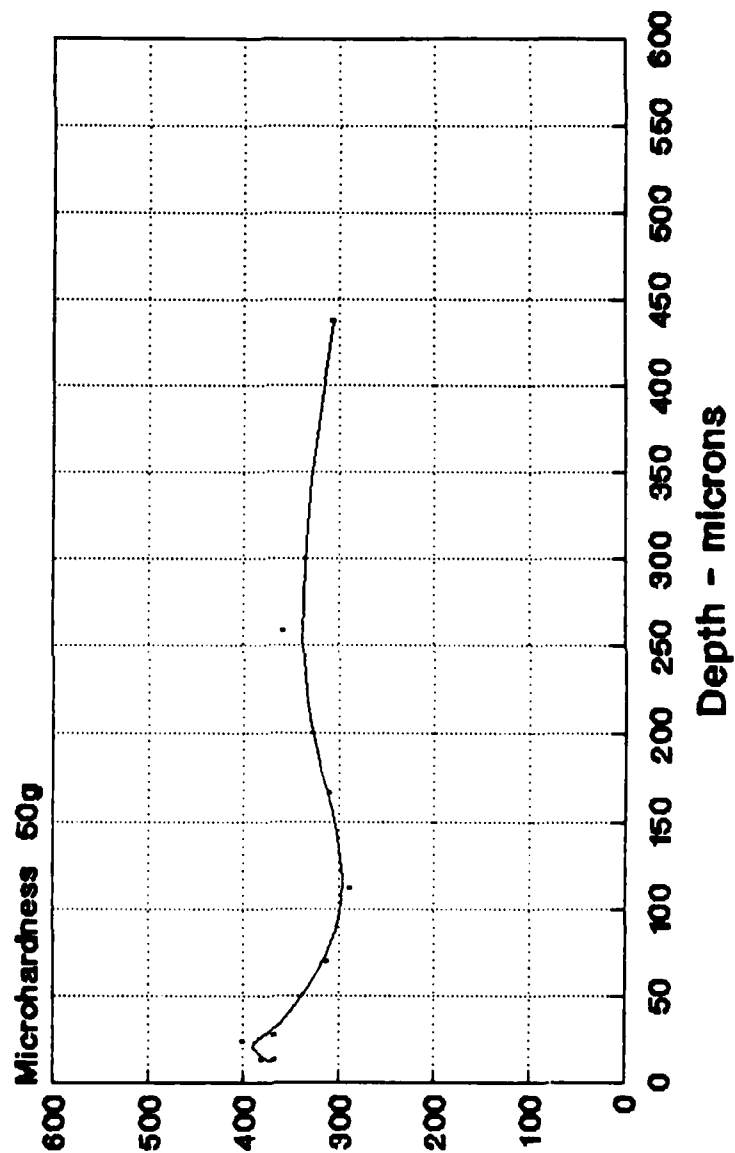


NATIONAL CENTRE OF TRIBOLOGY

# MICROHARDNESS DEPTH PROFILE HSSA 18/ NITROX #3

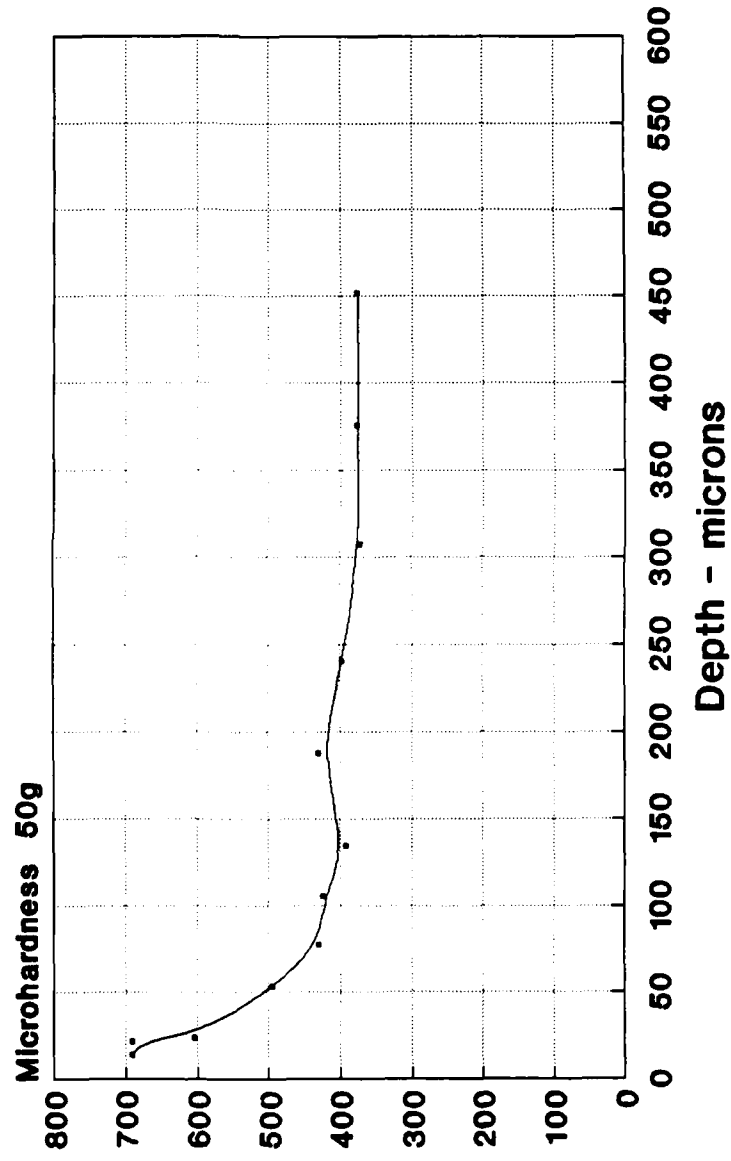


# MICROHARDNESS DEPTH PROFILE HSSA 19/PACK ALUMINISING #2



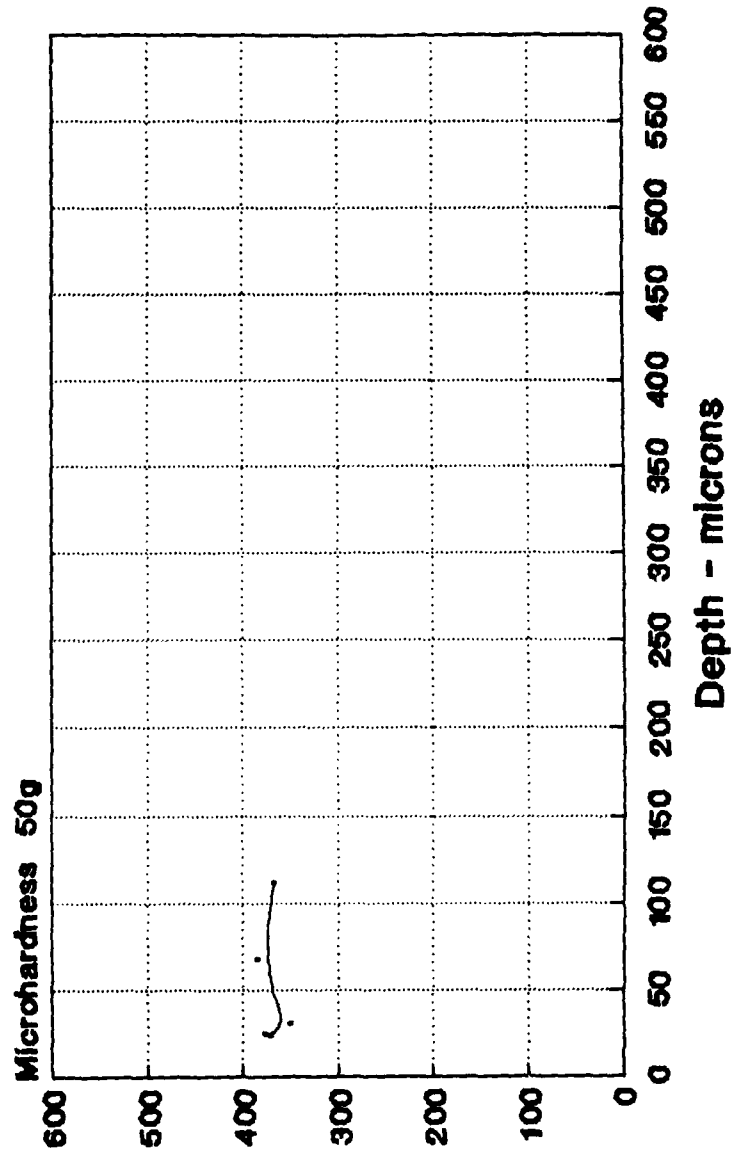
NATIONAL CENTRE OF TRIBOLOGY

# MICROHARDNESS DEPTH PROFILE HSSA 20/ CARBONITRIDED #1



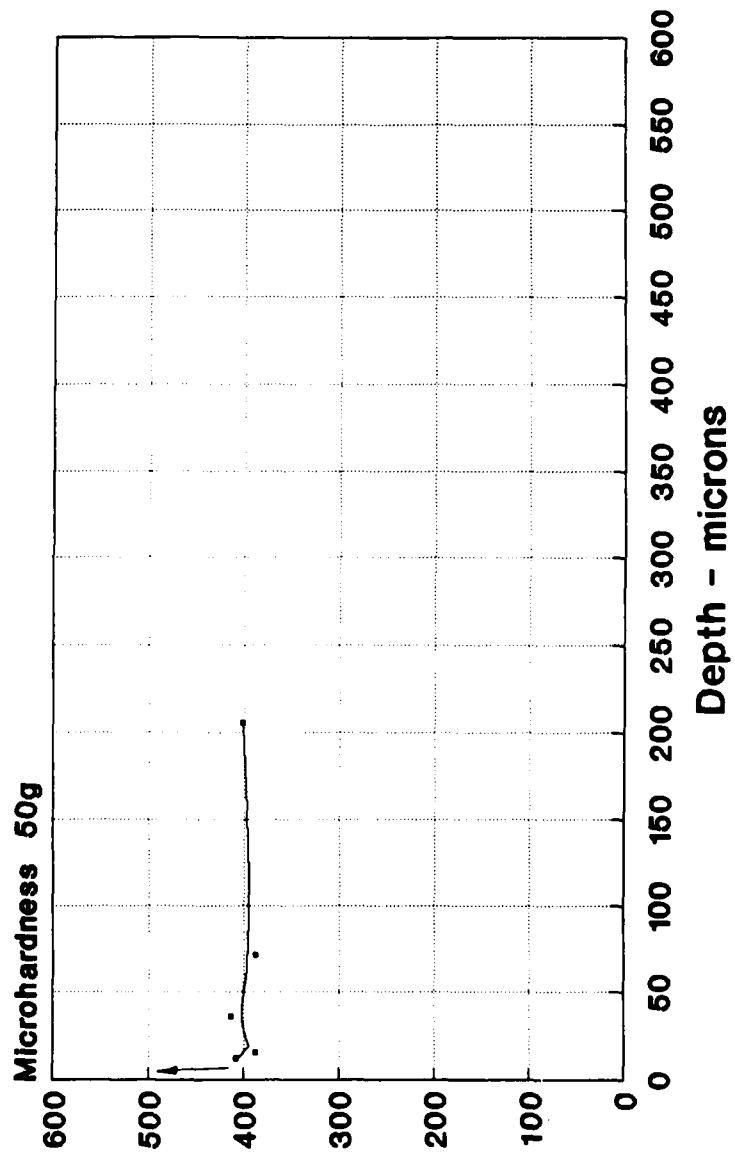
NATIONAL CENTRE OF TRIBOLOGY

**MICROHARDNESS DEPTH PROFILE**  
**HSSA 21/ DLC #1**



NATIONAL CENTRE OF TRIBOLOGY

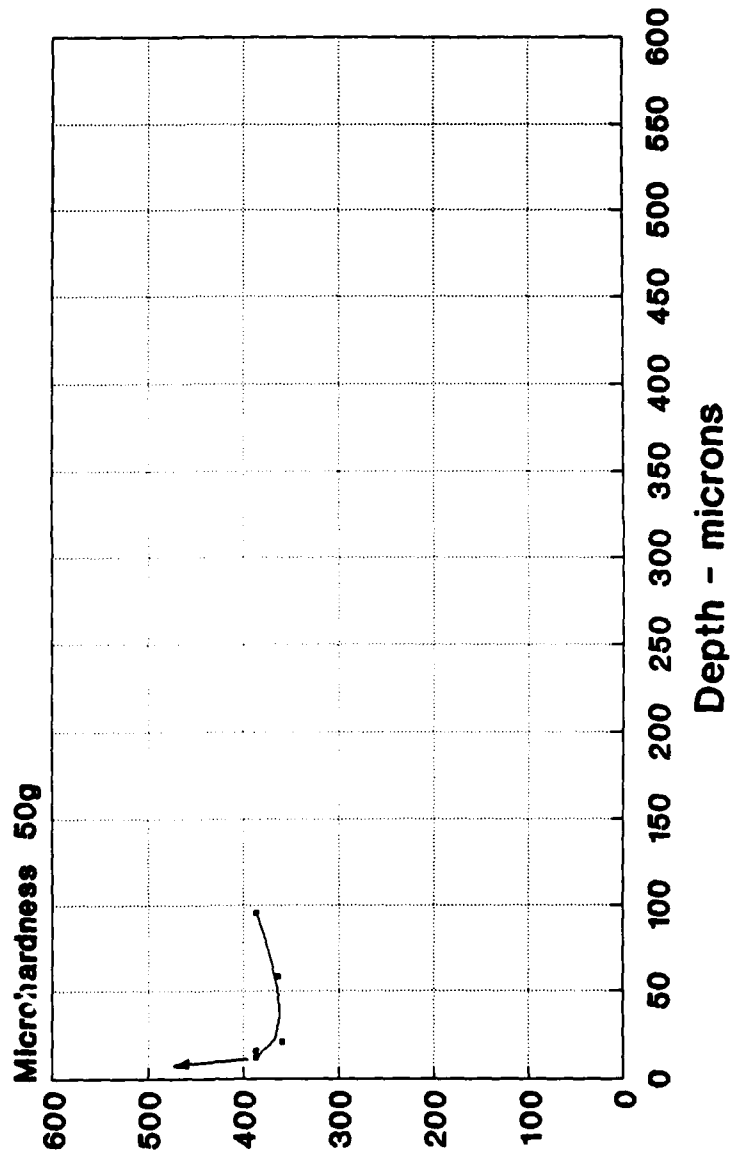
# MICROHARDNESS DEPTH PROFILE HSSA 22/TiN #3



NATIONAL CENTRE OF TRIBOLOGY

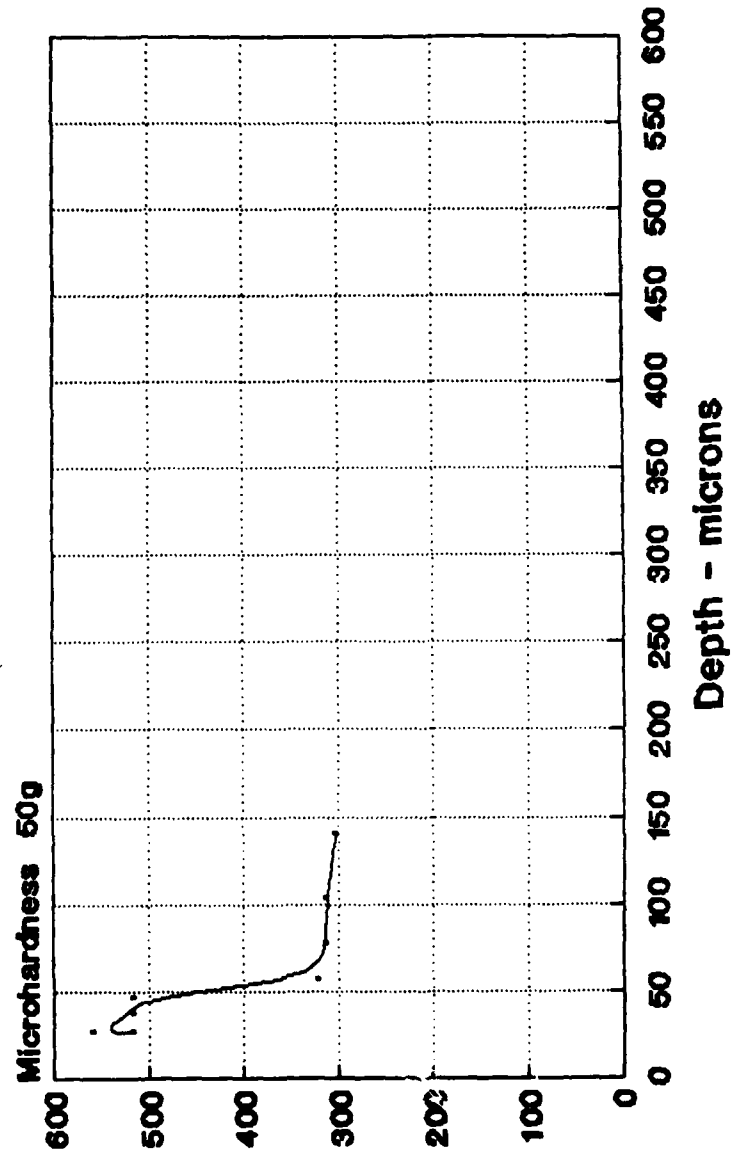


# MICROHARDNESS DEPTH PROFILE HSSA 23/ TiN/HfN MULTILAYER #1



NATIONAL CENTRE OF TRIBOLOGY

# MICROHARDNESS DEPTH PROFILE HSSA 24/ PACK ALUMINISING #3



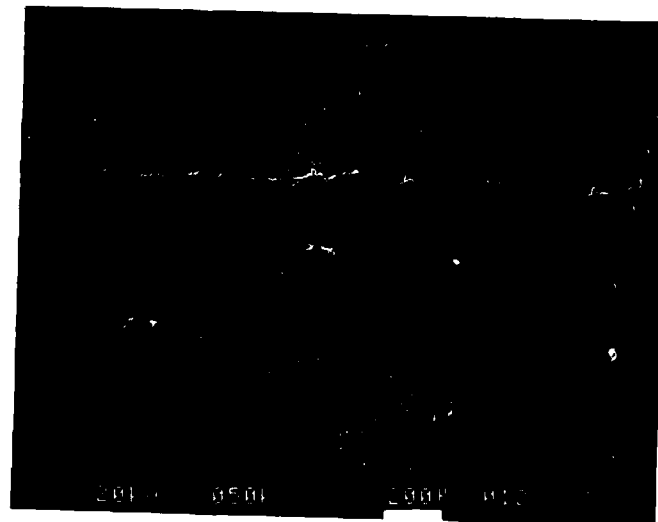
NATIONAL CENTRE OF TRIBOLOGY

**APPENDIX 4: 20N Wear Profiles and SEM Micrographs of Wear Tracks**

# HSSA 1: Solution Heat Treated

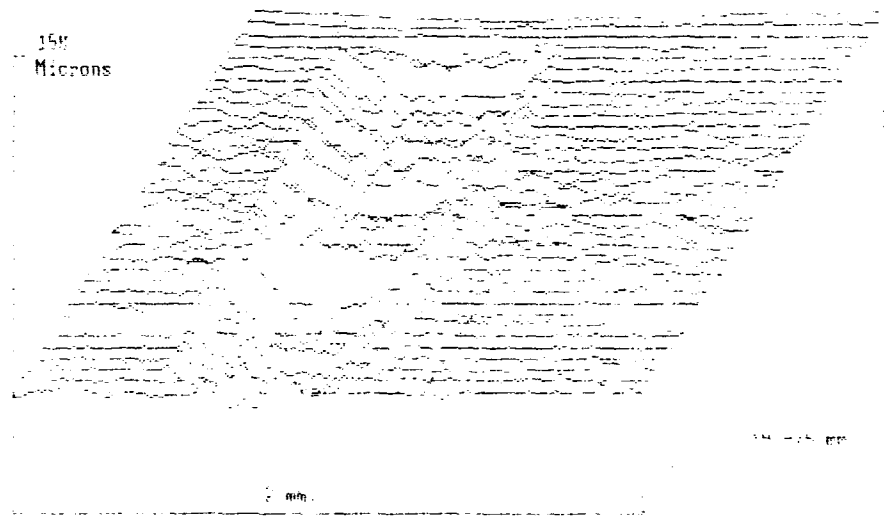
Data from b1155a-1a.dat  
Detrended

150  
Microns



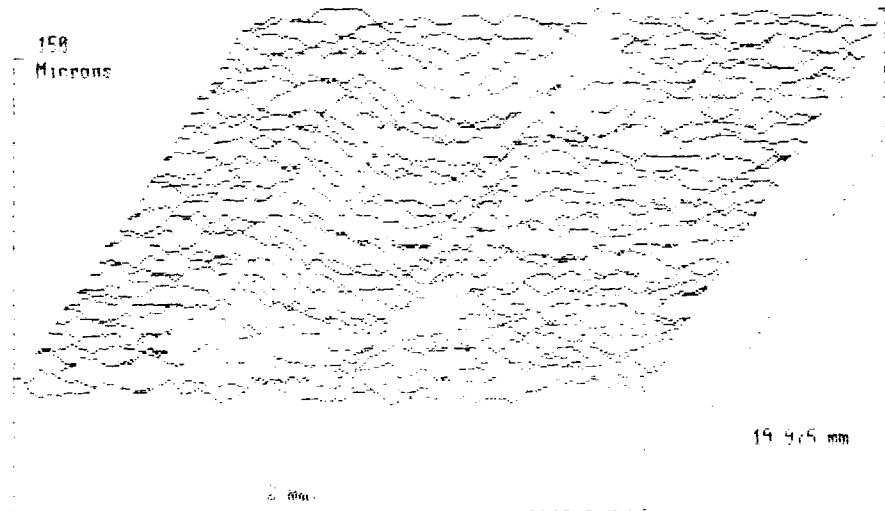
## HSSA 2: Hardened and Ground

Data from HSSA 2: Hardened and Ground  
Retained



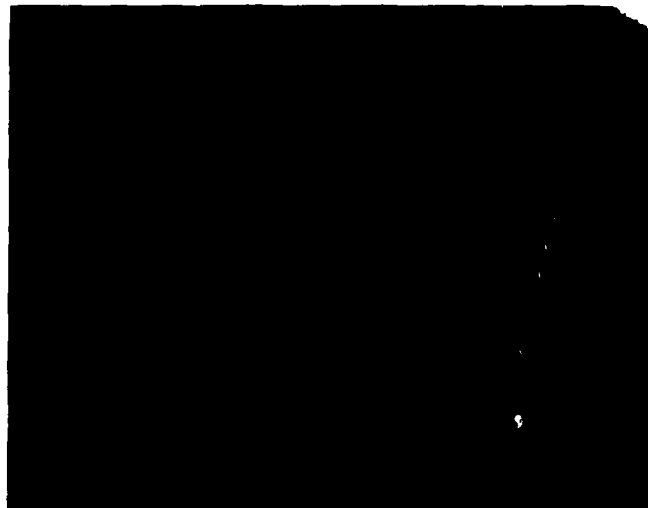
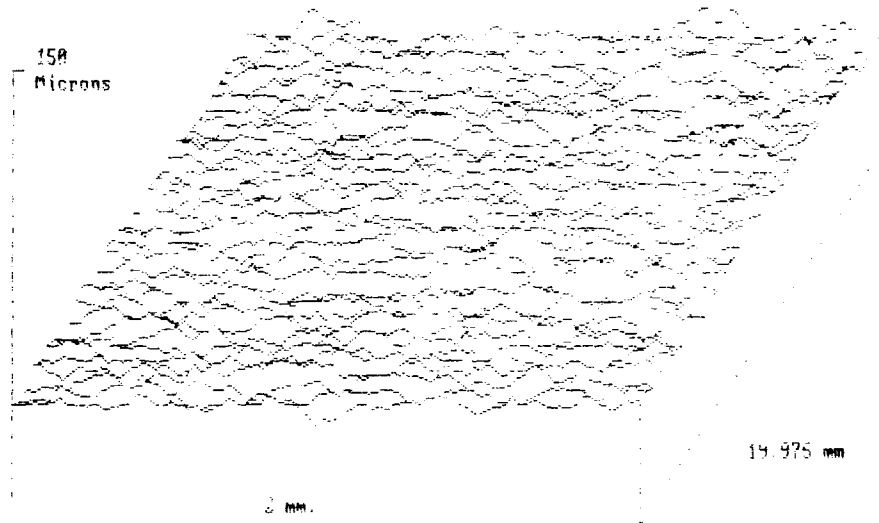
# HSSA3: Plasma Nitrocarburized 1

Data from h:hssa-2.dat  
Detrended



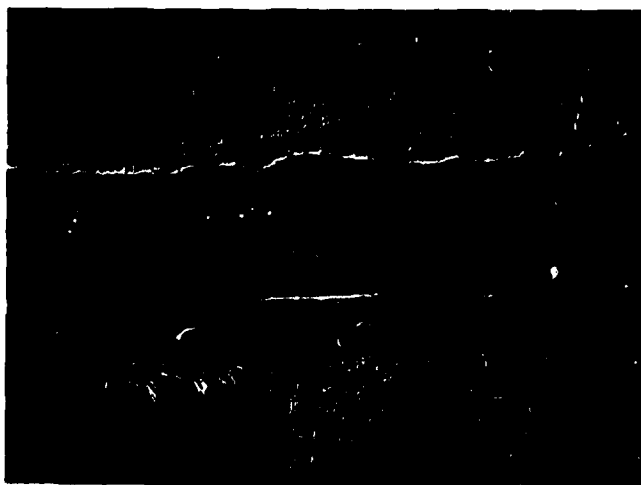
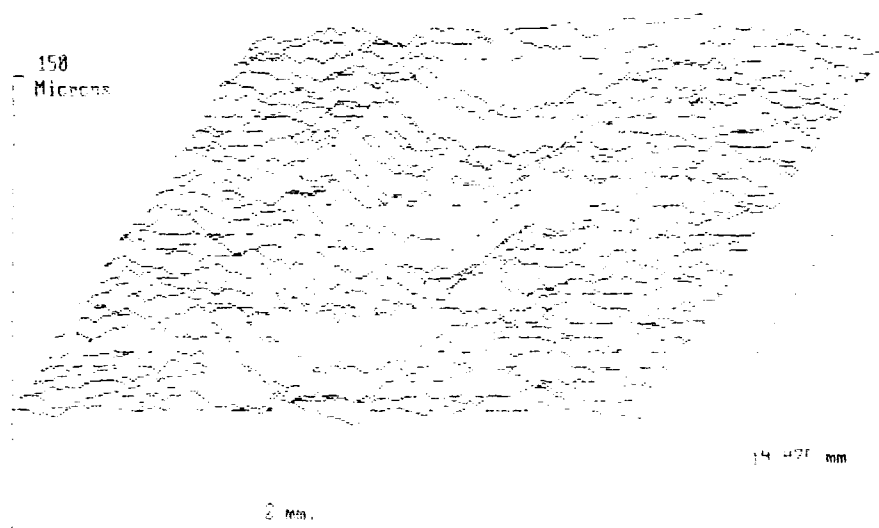
# HSSA4: Beta Nitrocarburized 1

Data from b:hssa-4.dat  
Detrended



# HSSA5: Ion Implanted 1

Data from h.hssa-5.dat  
Decruded



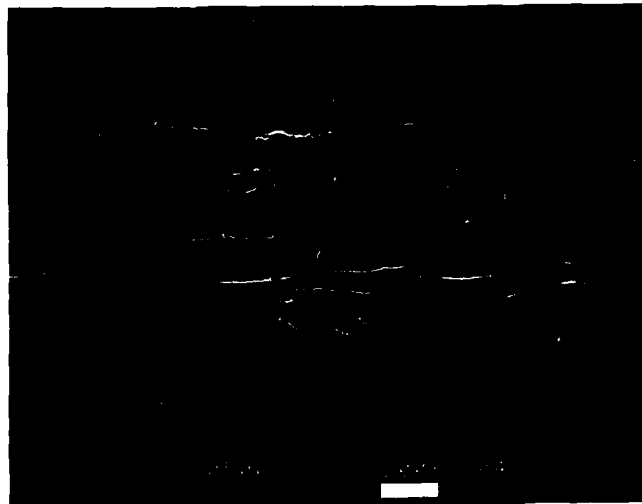


# HSSA 6: Ion Implanted 2

Data from h:hssa-6.dat  
Detrended

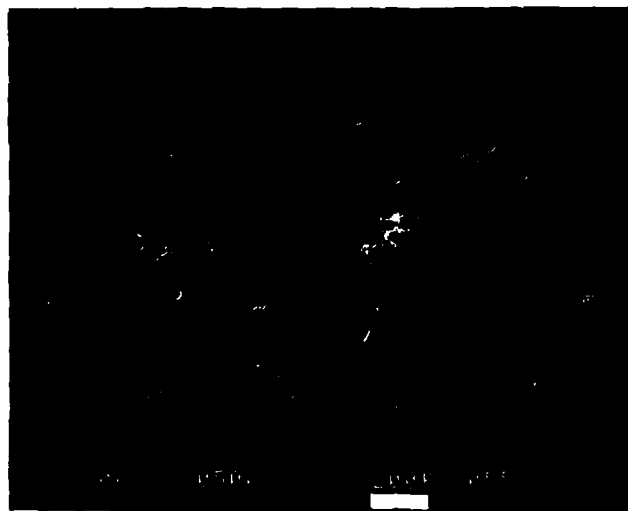
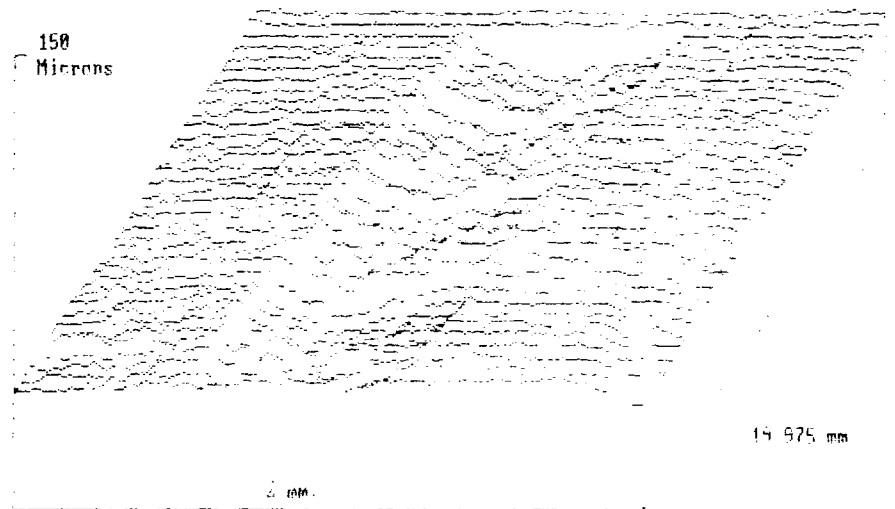


Figure 1: A 3D surface plot showing the topography of the ion-implanted surface. The plot displays a series of peaks and valleys, indicating a non-uniform surface profile. The vertical axis represents height, and the horizontal axes represent spatial coordinates.



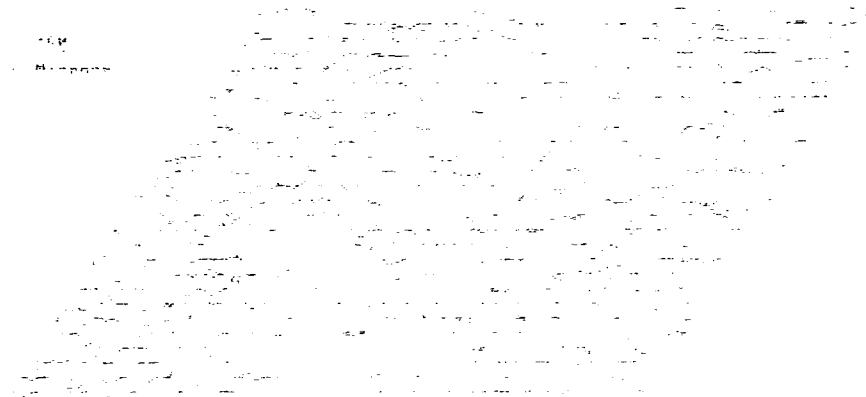
# HSSA7: Hard Anodised 1

Data from HSSA7-1-1  
Detrended



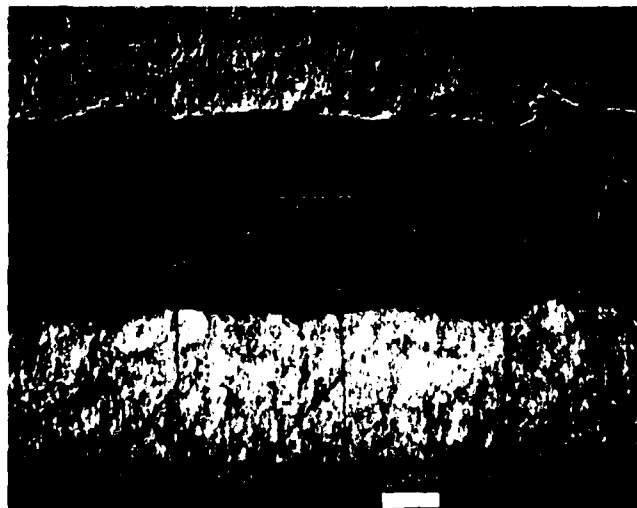
# HSSA8: Hard Anodised 2

Data from hsssa8.dat  
Downloaded



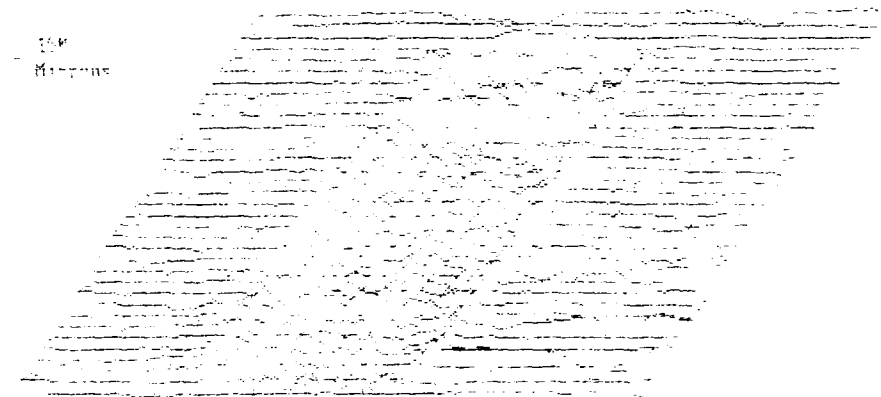
100 400 600

1000



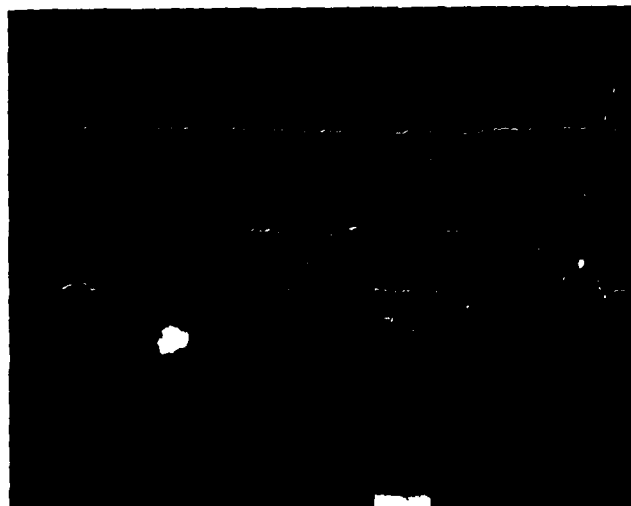
# HSSA9: Plasma Nitrocarburized 2

Data from sheet 9.dat  
Detrended



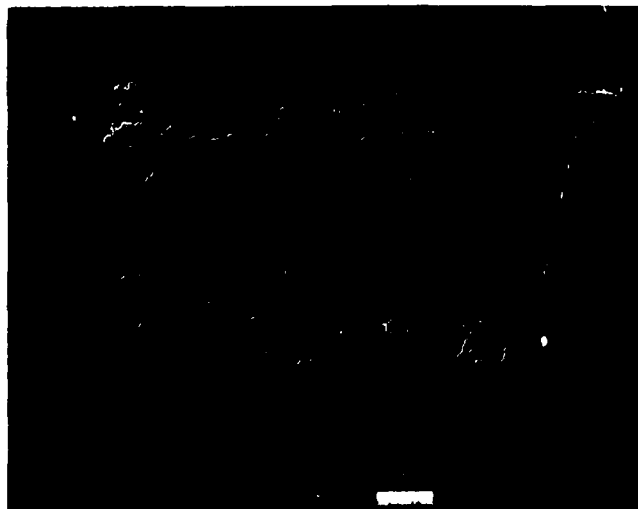
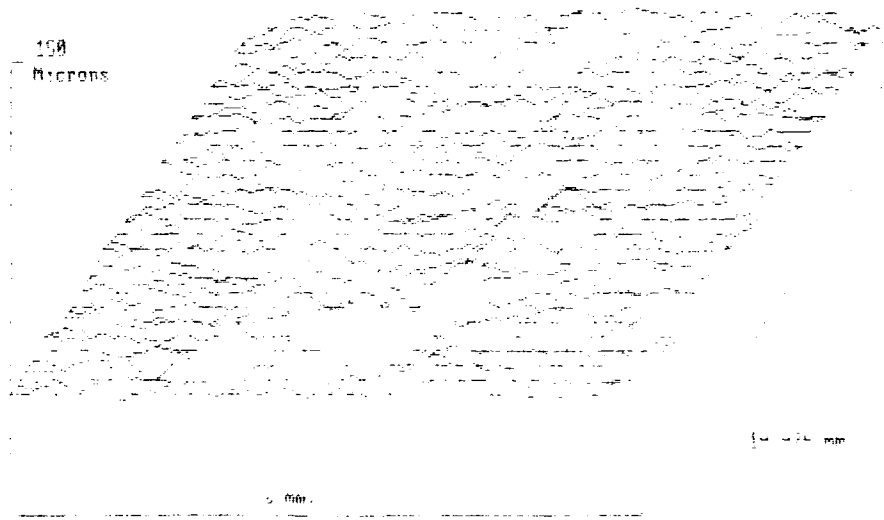
14 4-10 mm

1. data



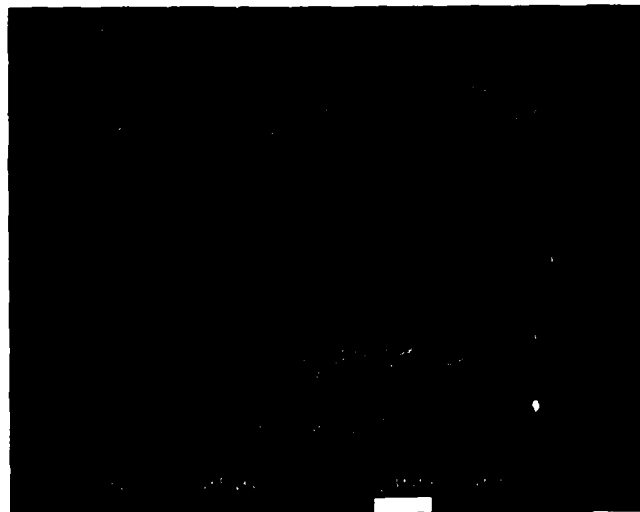
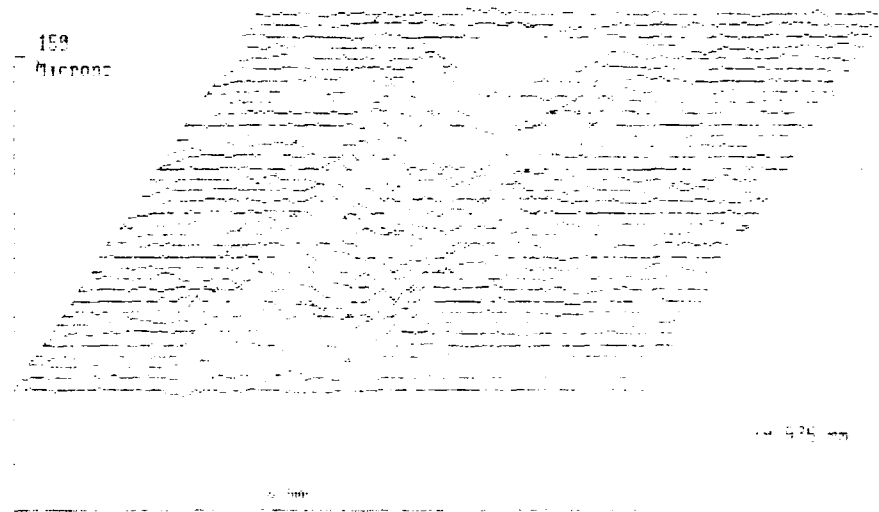
# HSSA 10: Hard Anodised 3

Data from HSSA 10.101  
Defended



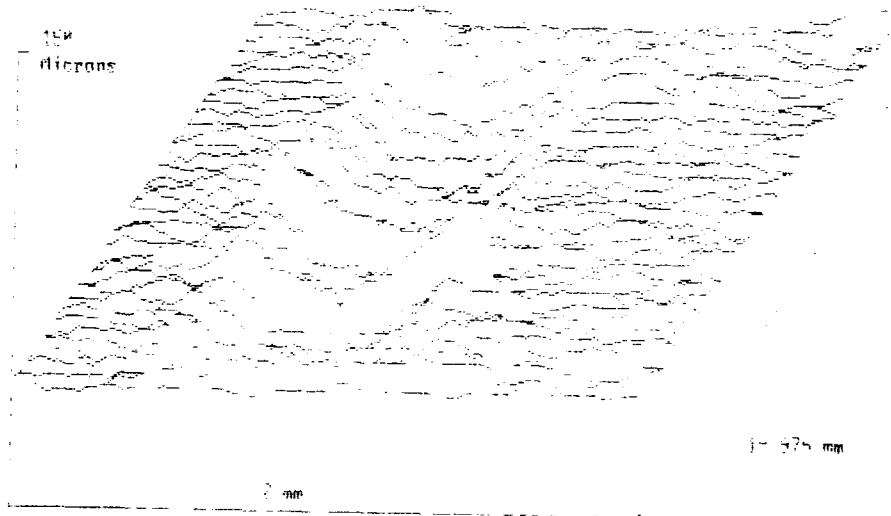
# HSSA 11: Hard Anodised 4

Data from b:hssa-11.dat  
Detrended



# HSSA 12: Plasma Nitrided 1

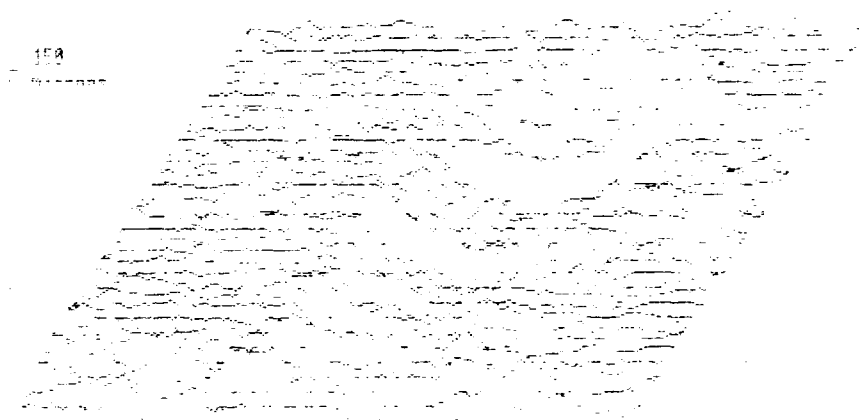
Data from h:hssa-12.dat  
Detrended



## HSSA 13: Plasma Nitrided 2

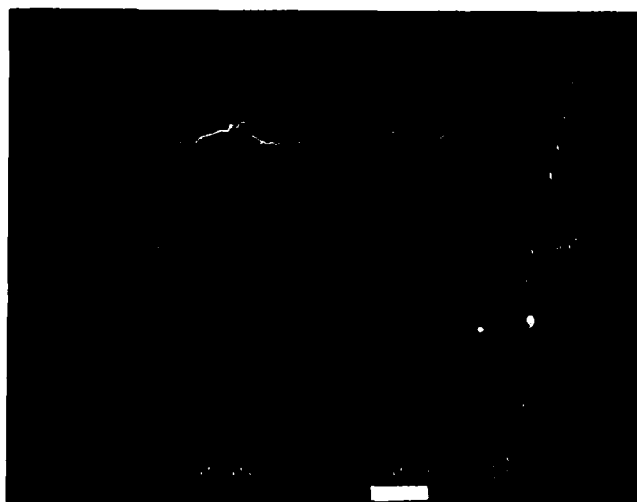
Data from h.hssa 13.dat  
Detrended

150  
0.000000



12.500000

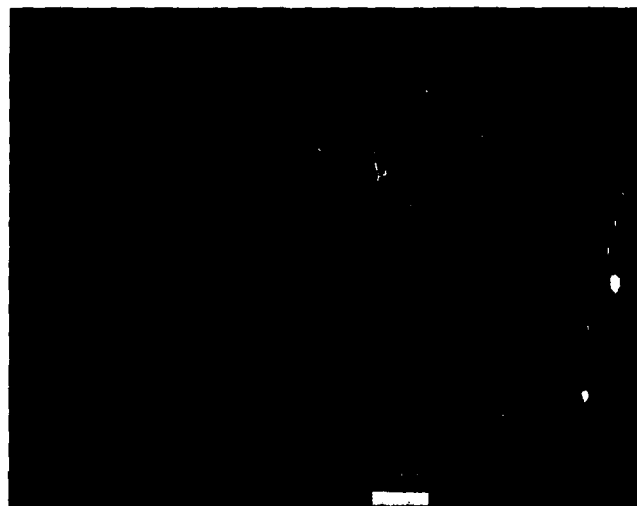
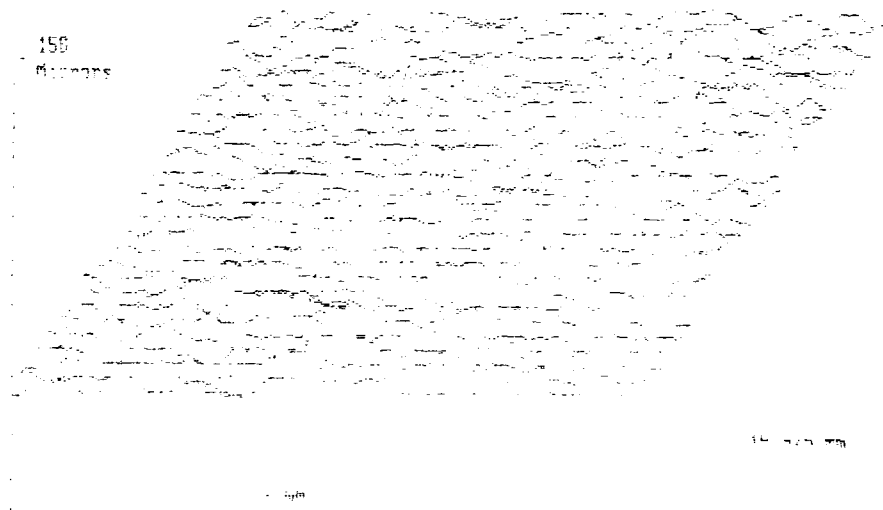
6 min





# HSSA 14: High Temperature Nitrocarburized 1

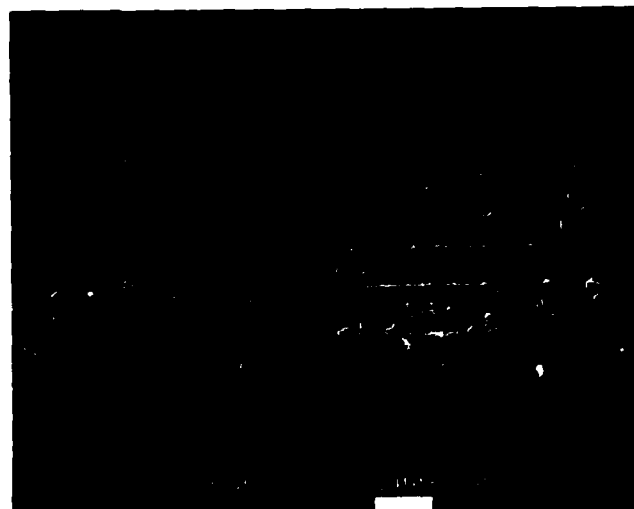
Specimen from HSSA 14.231  
Detrended



I  
HSSA15: Nitrosc 1

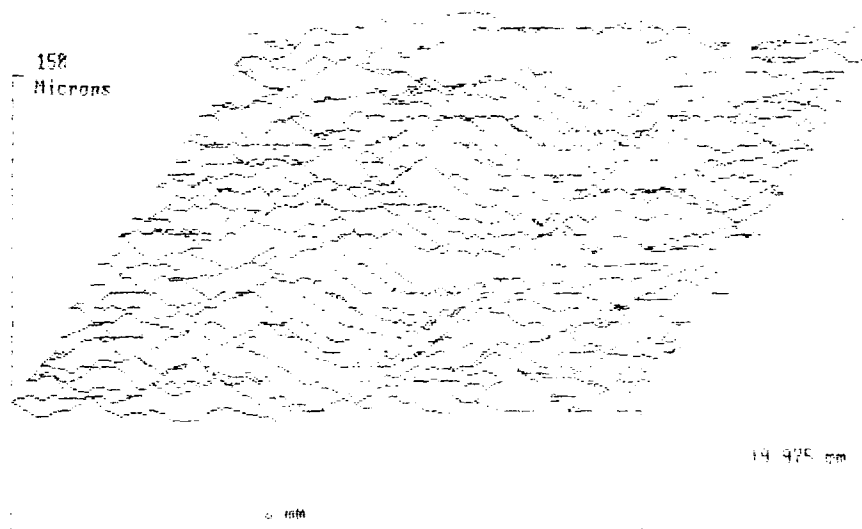
Data from hhsca 10.dat  
Described

15M  
1000000



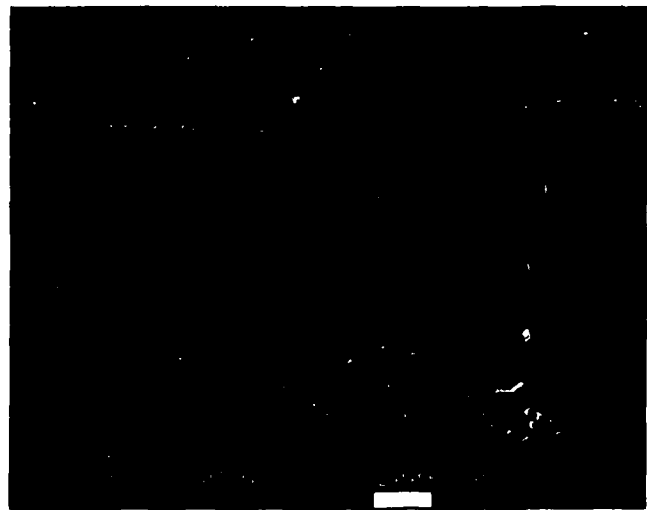
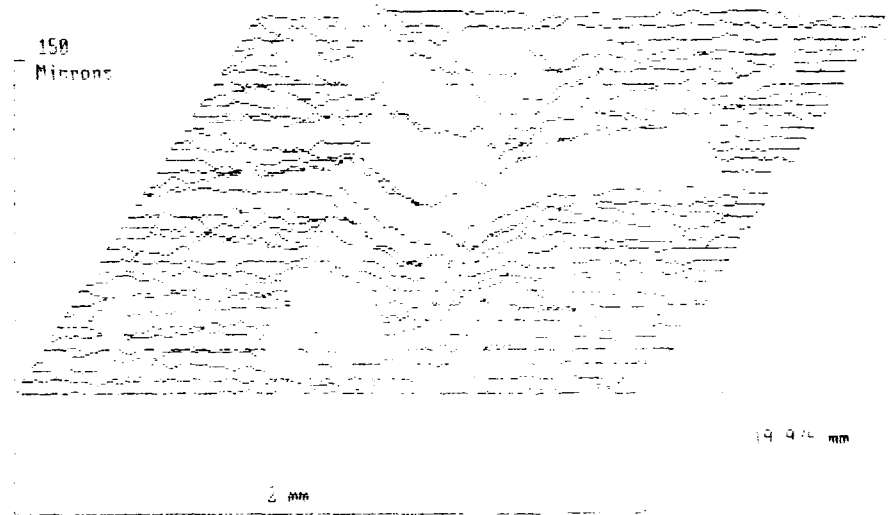
# HSSA 17: Nitrosc 2

Data from hihssa-17.dat  
Detrended



# HSSA 18: Nitrosc 3

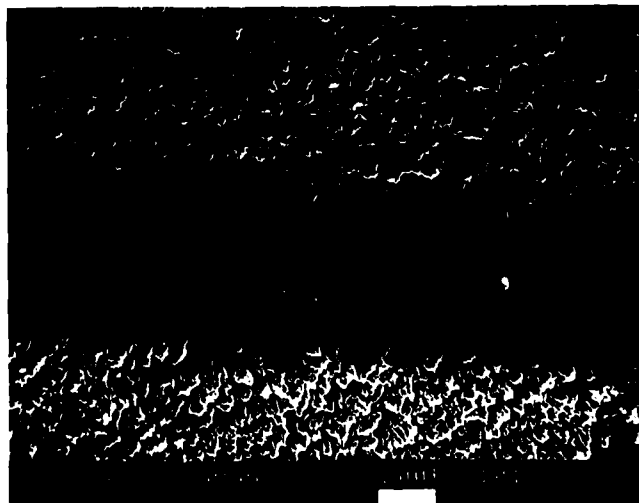
Data from h:hssa-18.dai  
Detrended



## HSSA 19: Pack Aluminising 2

Data from hsssa 19.dat  
Unprocessed

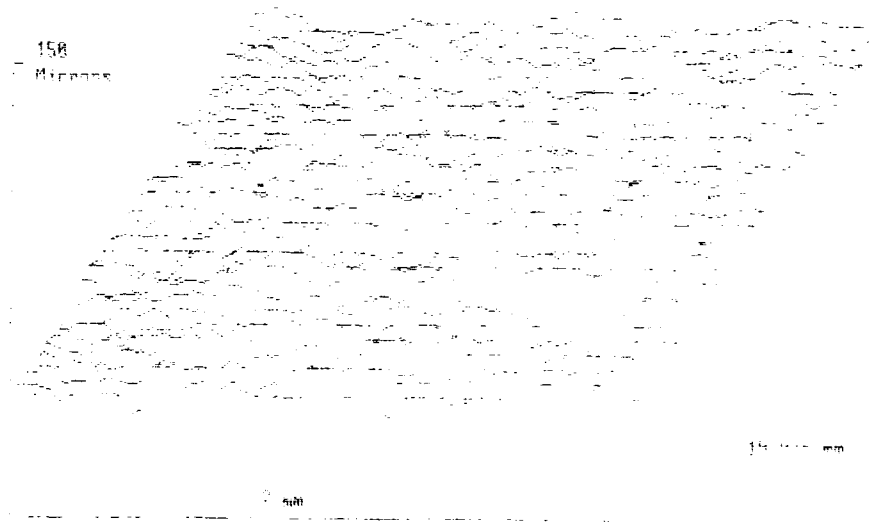
150  
microns



# HSSA20: Gas Carbonitriding 1

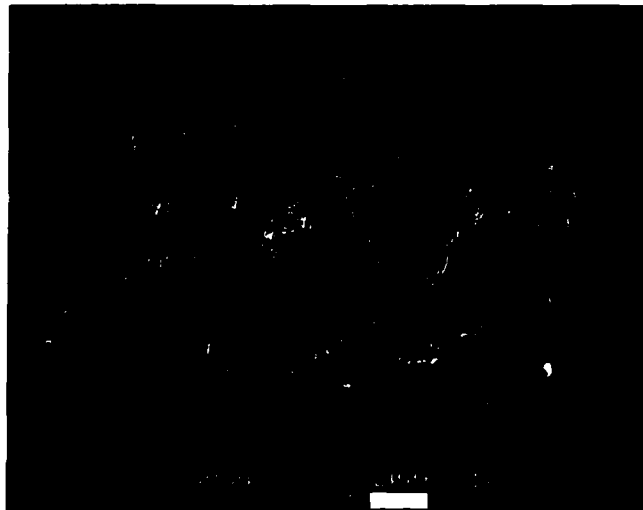
Data from bhsca 20.dat  
Detrended

158  
Mippppp



1/10/10 mm

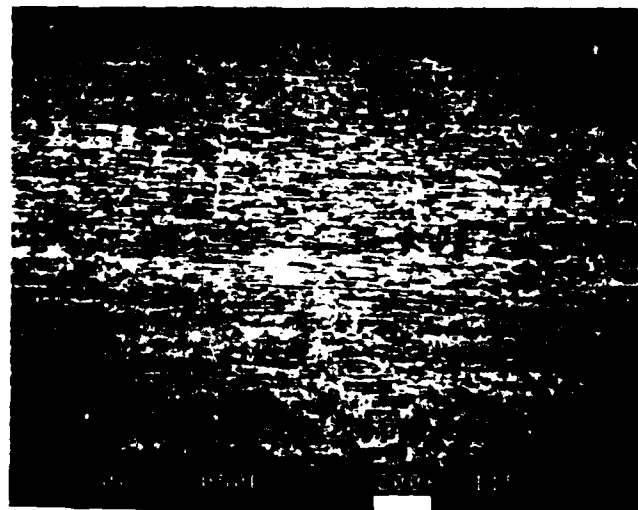
2 500



# HSSA 21: Diamond-like Carbon 1

Data from HSSA-21.txt  
Detected

158  
microns

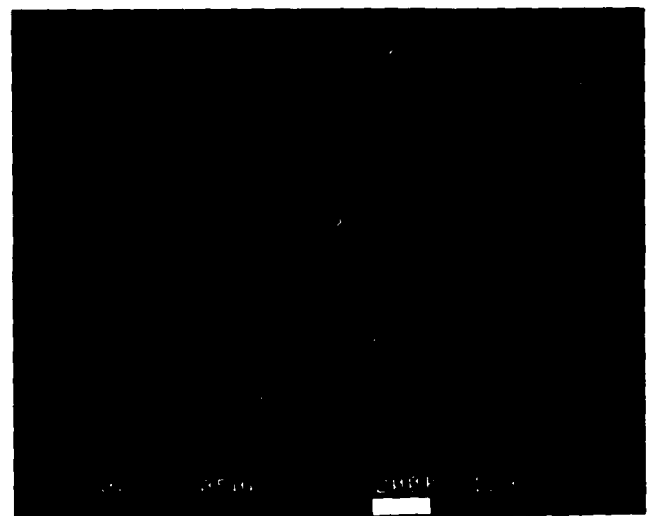


5  
3  
2

## HSSA 22: TiN Reactive Sputter

DATA FROM SIMULATED SPUTTER  
CONTINUED

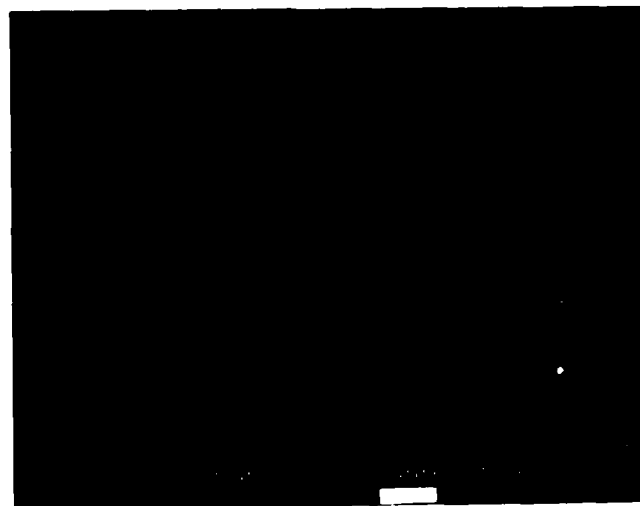
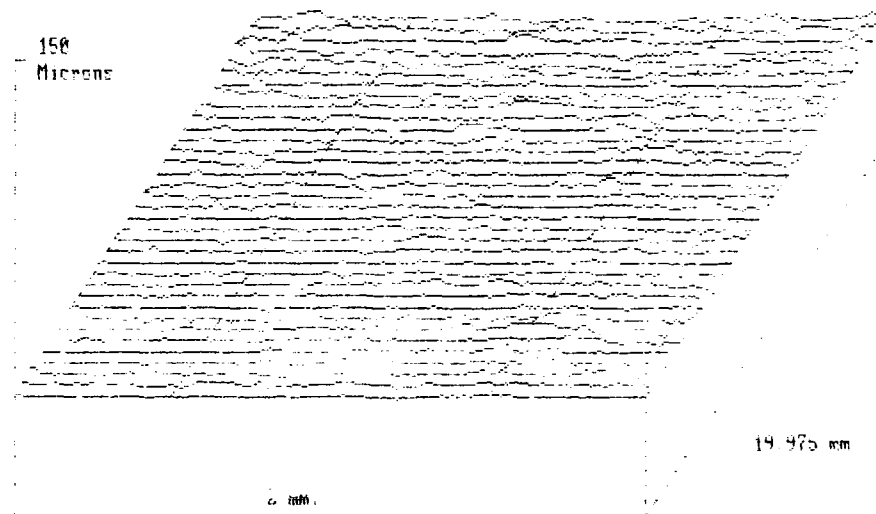
100  
11000000  
12000000  
13000000  
14000000  
15000000  
16000000  
17000000  
18000000  
19000000  
20000000  
21000000  
22000000  
23000000  
24000000  
25000000  
26000000  
27000000  
28000000  
29000000  
30000000  
31000000  
32000000  
33000000  
34000000  
35000000  
36000000  
37000000  
38000000  
39000000  
40000000  
41000000  
42000000  
43000000  
44000000  
45000000  
46000000  
47000000  
48000000  
49000000  
50000000  
51000000  
52000000  
53000000  
54000000  
55000000  
56000000  
57000000  
58000000  
59000000  
60000000  
61000000  
62000000  
63000000  
64000000  
65000000  
66000000  
67000000  
68000000  
69000000  
70000000  
71000000  
72000000  
73000000  
74000000  
75000000  
76000000  
77000000  
78000000  
79000000  
80000000  
81000000  
82000000  
83000000  
84000000  
85000000  
86000000  
87000000  
88000000  
89000000  
90000000  
91000000  
92000000  
93000000  
94000000  
95000000  
96000000  
97000000  
98000000  
99000000  
100000000





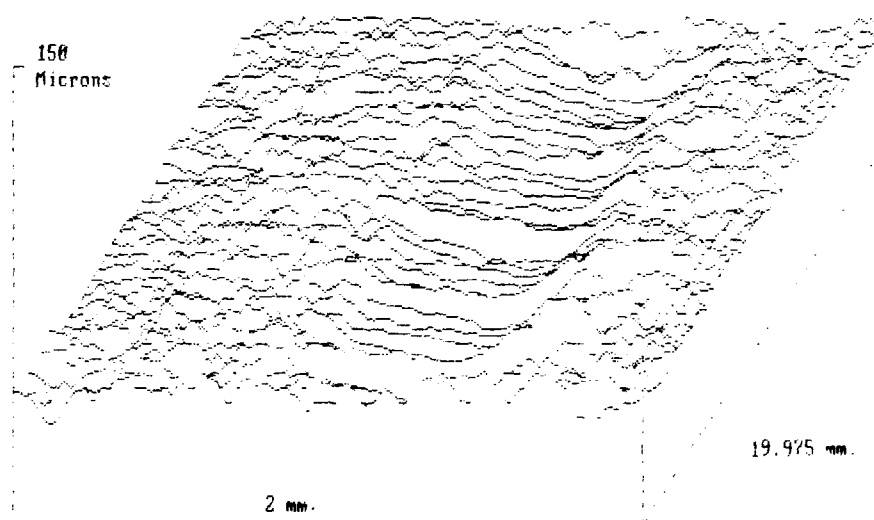
# HSSA 23: TiN/HfN Multilayer

Data from HSSA-23.dat  
Detrended

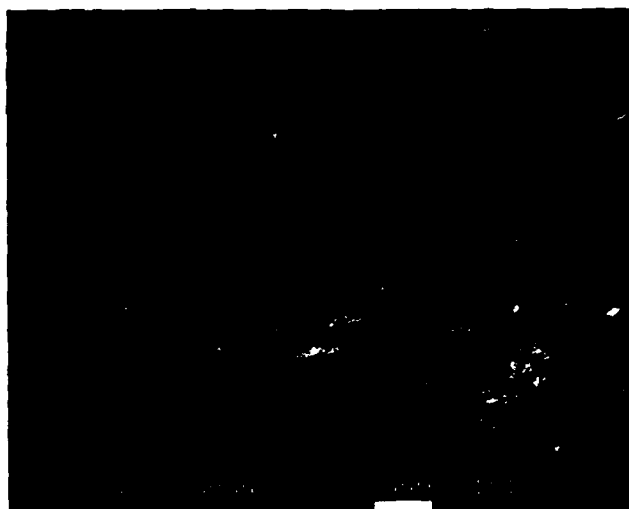


# HSSA 24: Pack Aluminising 3

Data from h:hssa-24.dat  
Detrended



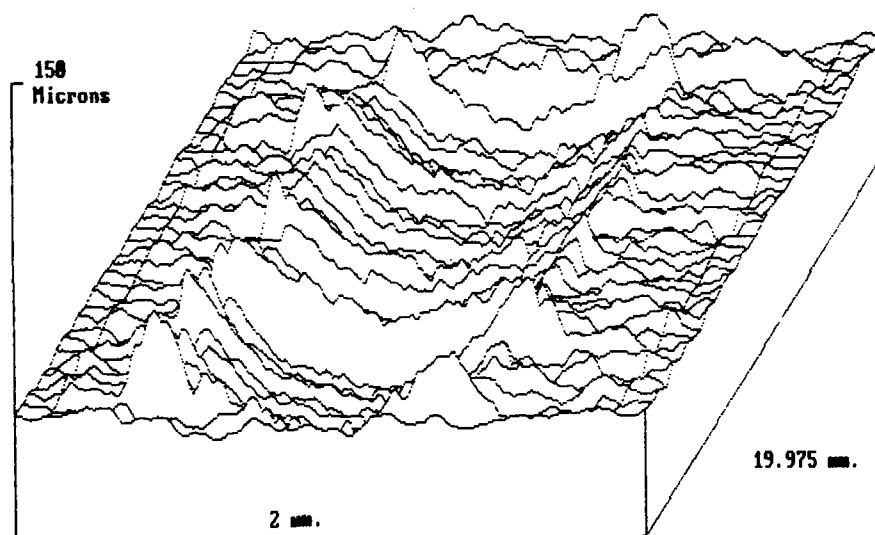
h:hssa-24.dat: h:hssa-24.dat  
h:hssa-24.dat: h:hssa-24.dat  
h:hssa-24.dat: h:hssa-24.dat



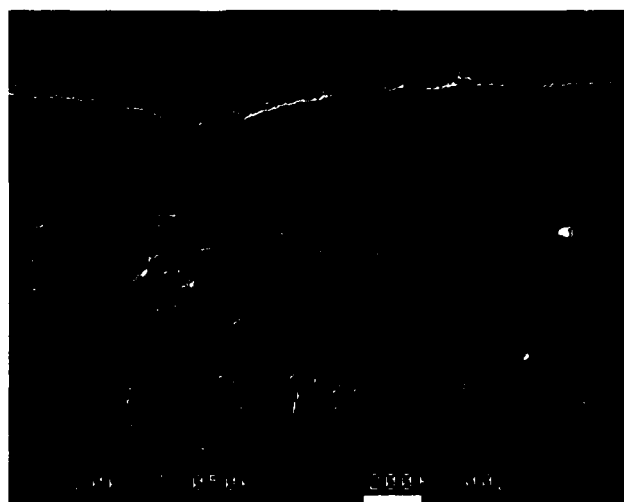
**APPENDIX 5: 50N Wear Profiles and SEM Micrographs of Wear Tracks**

# HSSA1: Solution Heat Treated

Data from h:hssa1.dat  
Detrended

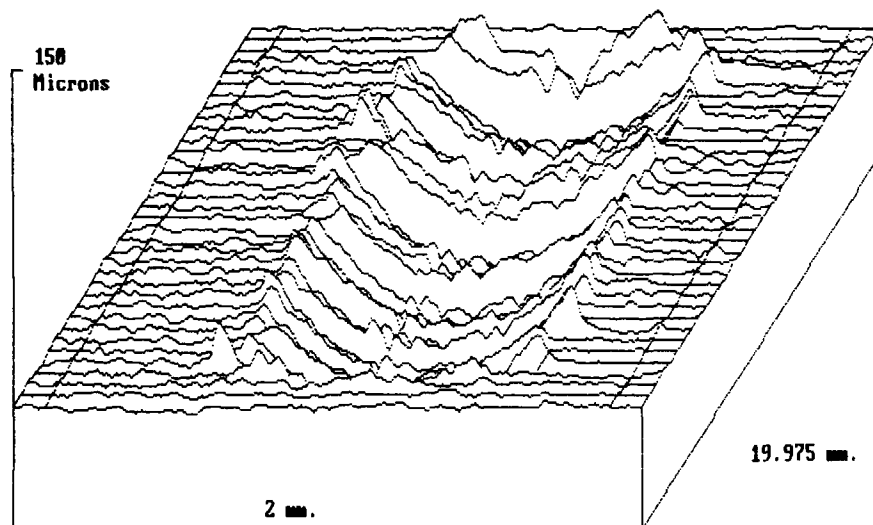


Wear volume in cubic millimetres  
Above datum    Below datum    Net loss  
.0456357    .2335793    .1879436

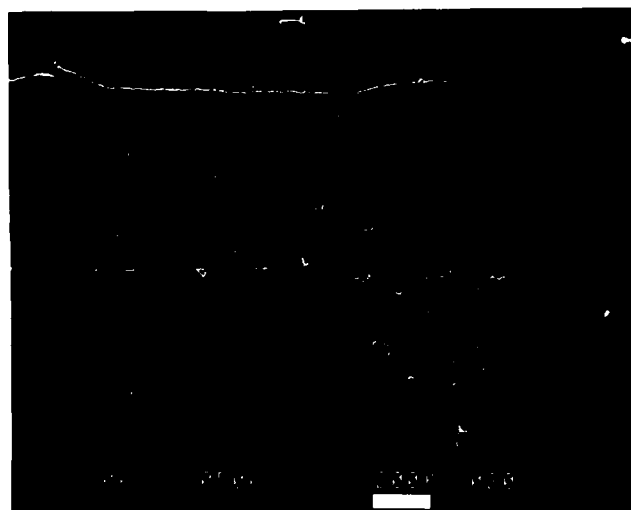


## HSSA2: Hardened and Ground

Data from h:hssa2.dat  
Detrended

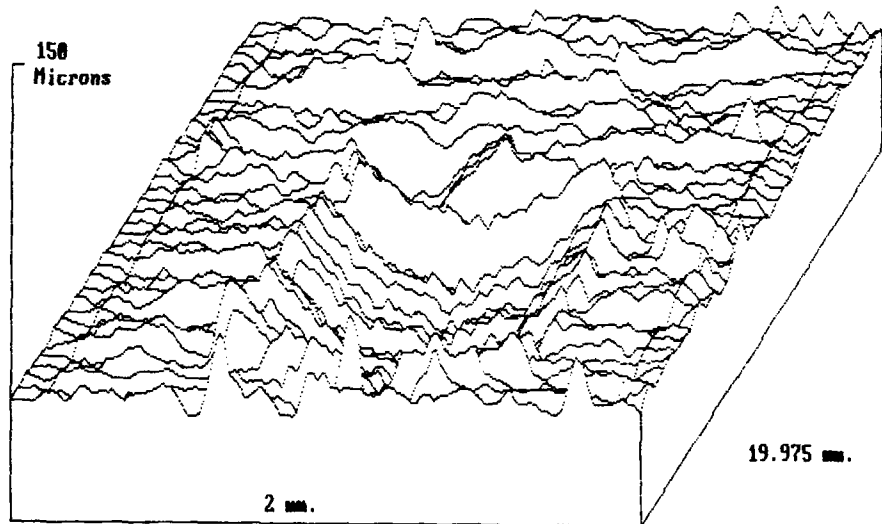


Wear volume in cubic millimetres  
Above datum    Below datum    Net loss  
1.857176E-02    .2437241    .2251523

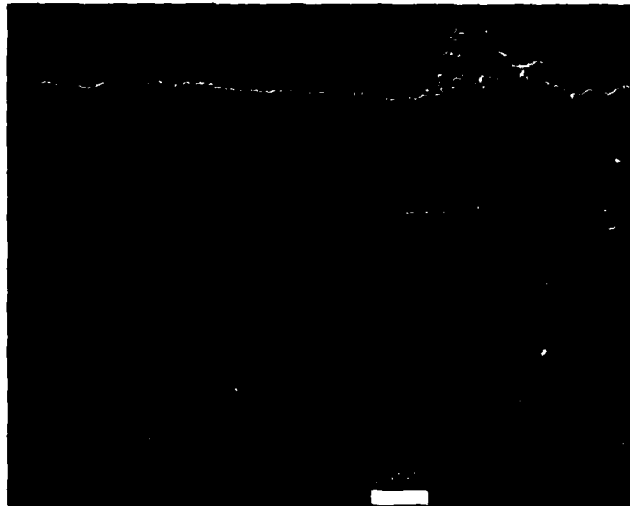


# HSSA3: Plasma Nitrocarburized 1

Data from h:hssa3.dat  
Detrended



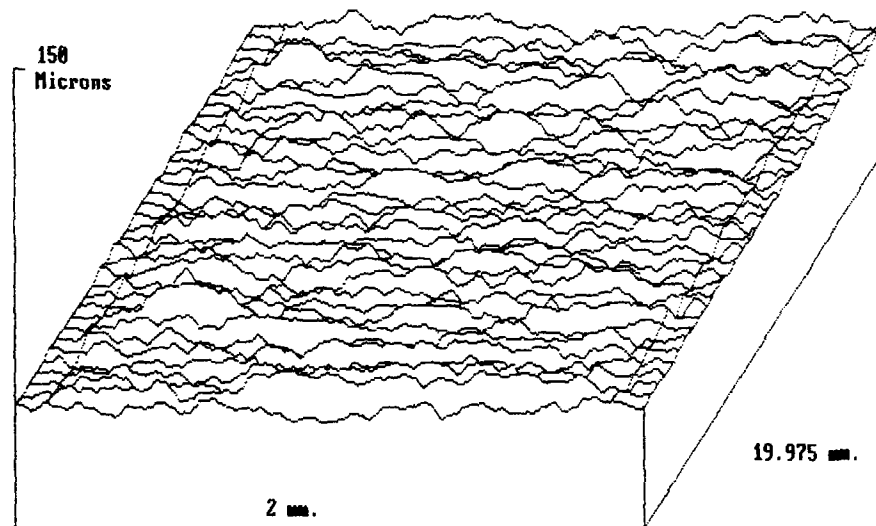
Wear volume in cubic millimetres  
Above datum    Below datum    Net loss  
5.616054E-02    .1875458    .1313852



# HSSA4: Beta Nitrocarburized 1

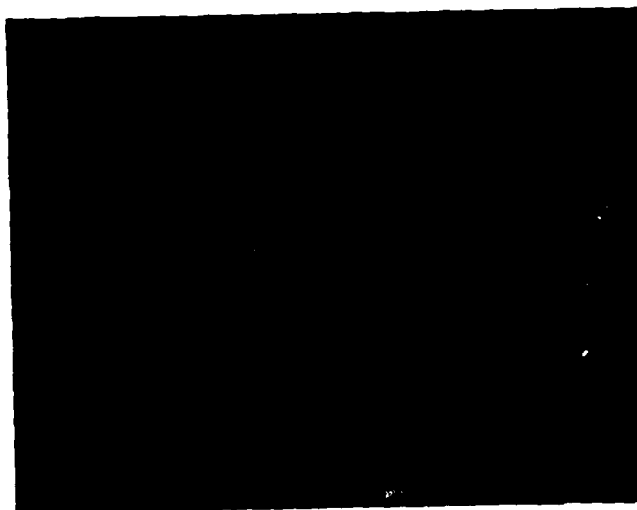
Data from h:hssa4.dat

Detrended



Wear volume in cubic millimetres

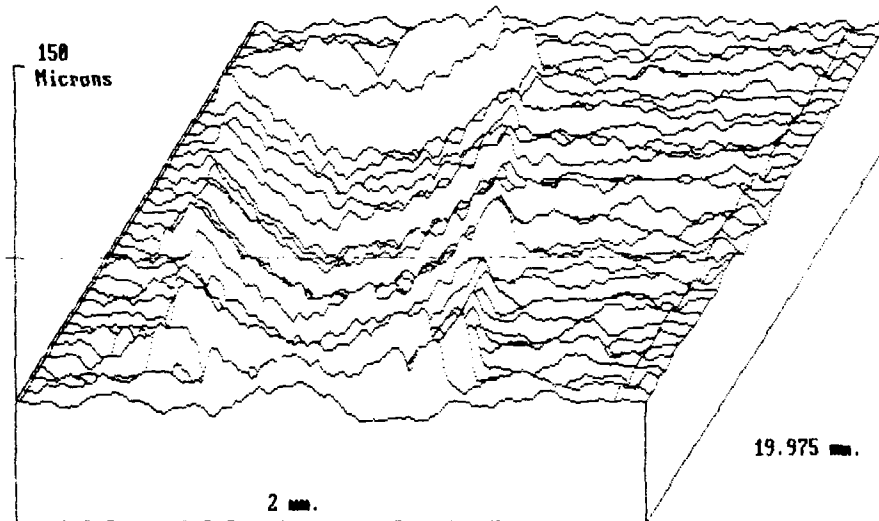
Above datum	Below datum	Net loss
3.921508E-02	3.531782E-02	-3.897257E-03



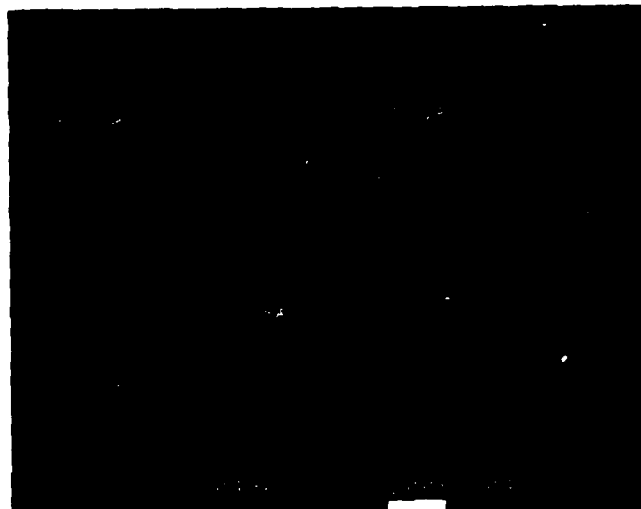
SCAR

# HSSA 5: Ion Implanted 1

Data from b:hssa5.dat  
Detrended



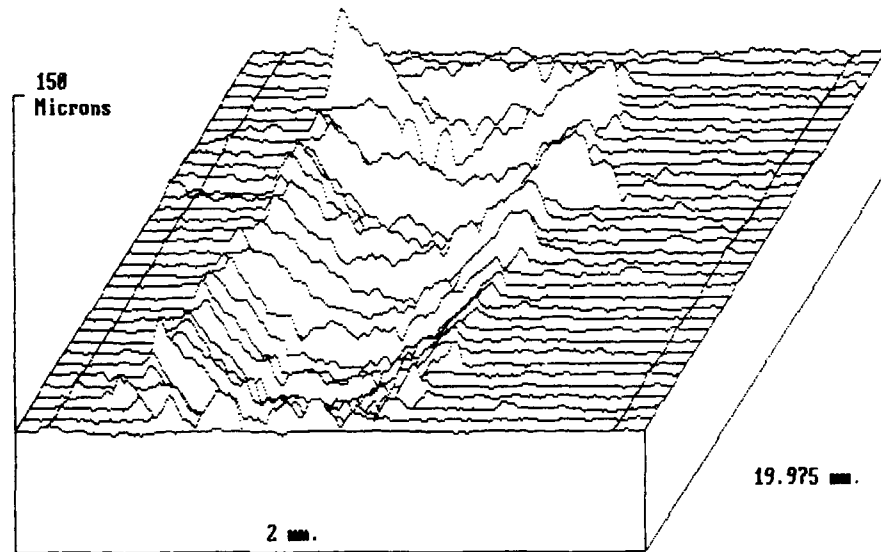
Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
4.209065E-02      .2399547      .1978641



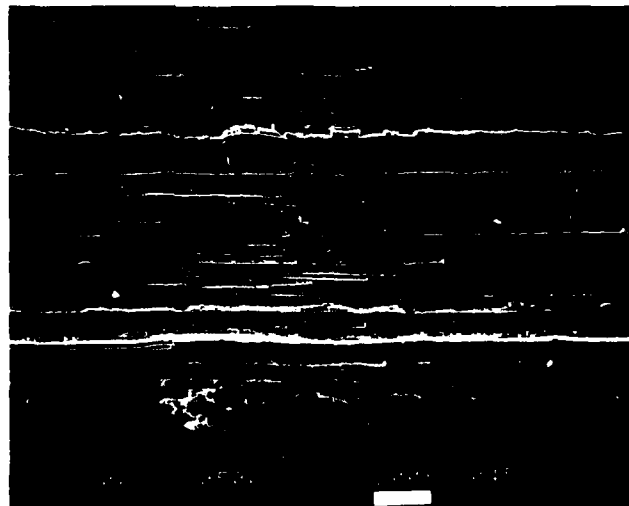


# HSSA 6: Ion Implanted 2

Data from h:hssa6.dat  
Detrended

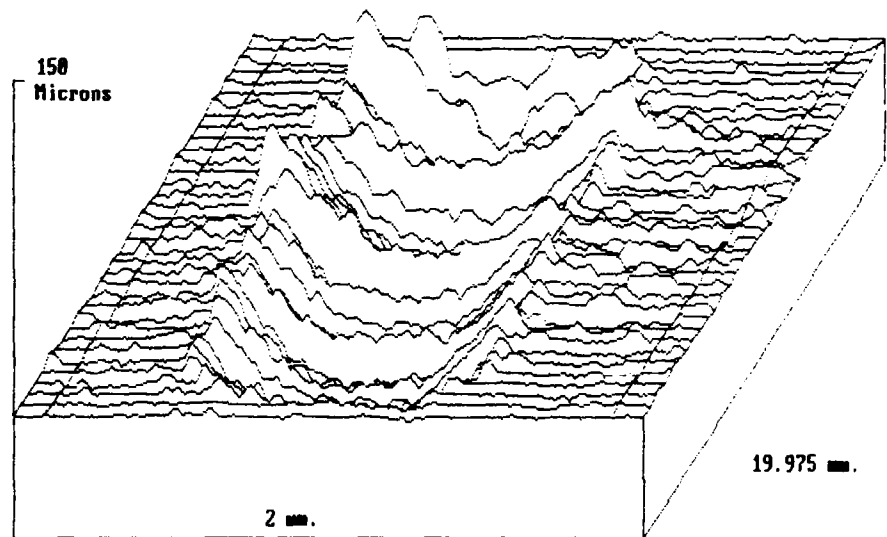


Wear volume in cubic millimetres  
Above datum    Below datum    Net loss  
2.041939E-02    .2303723    .2099529



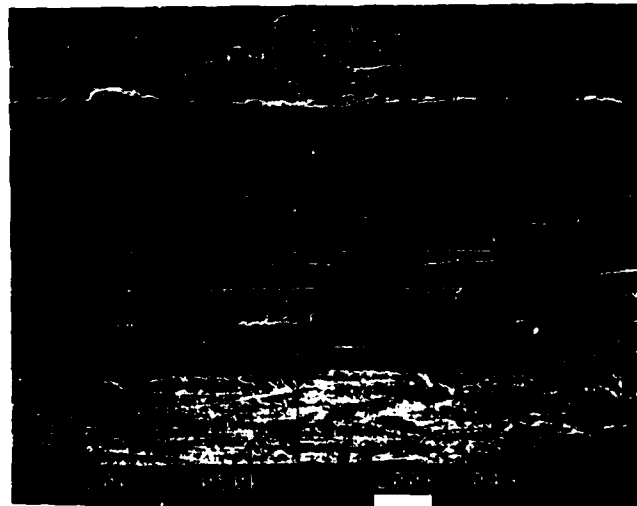
# HSSA7: Hard Anodised 1

Data from h:hssa7.dat  
Detrended



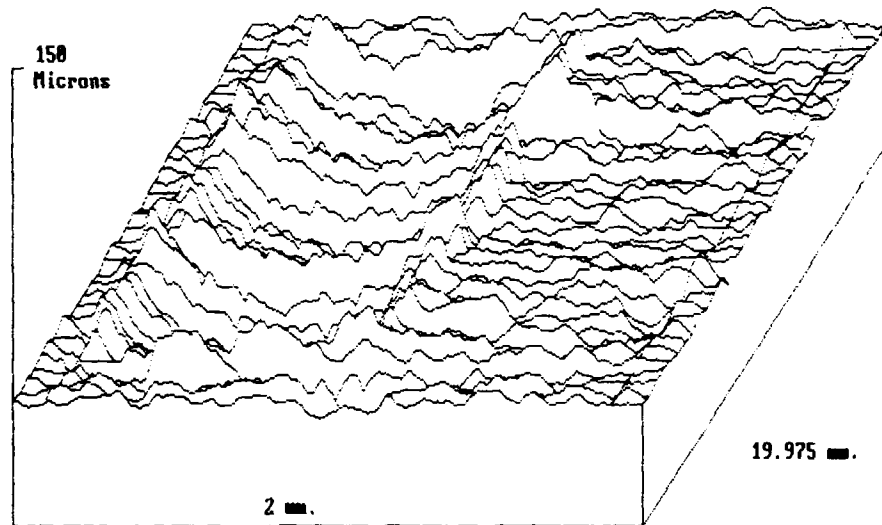
Wear volume in cubic millimetres

Above datum	Below datum	Net loss
2.642487E-02	.2412461	.2148212



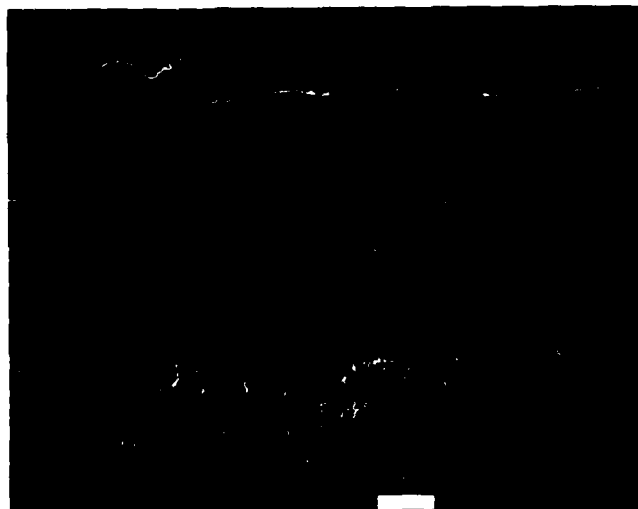
# HSSA8: Hard Anodised 2

Data from b:hssa8.dat  
Detrended



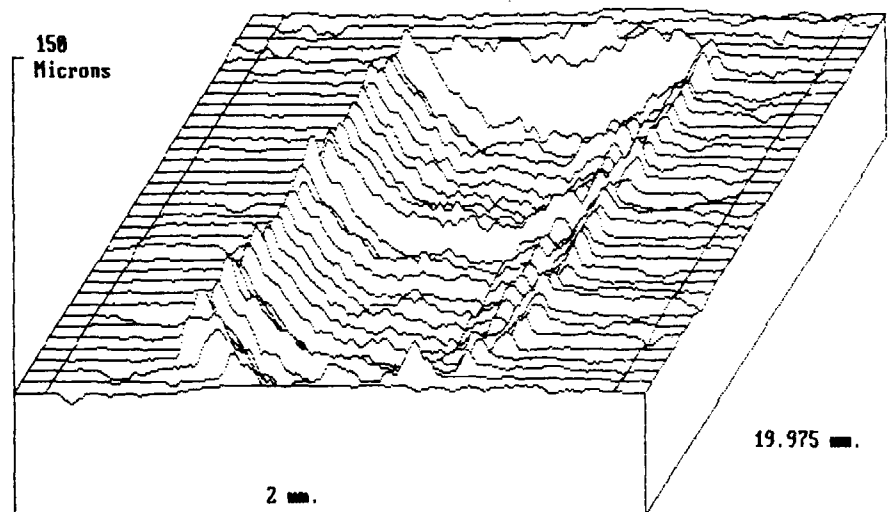
Wear volume in cubic millimetres

Above datum	Below datum	Net loss
4.153366E-02	.2389727	.197439



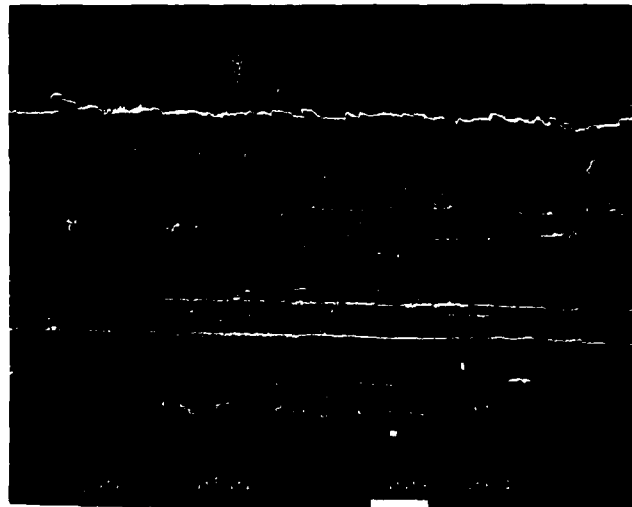
# HSSA 9: Plasma Nitrocarburized 2

Data from b:hssa9.dat  
Detrended



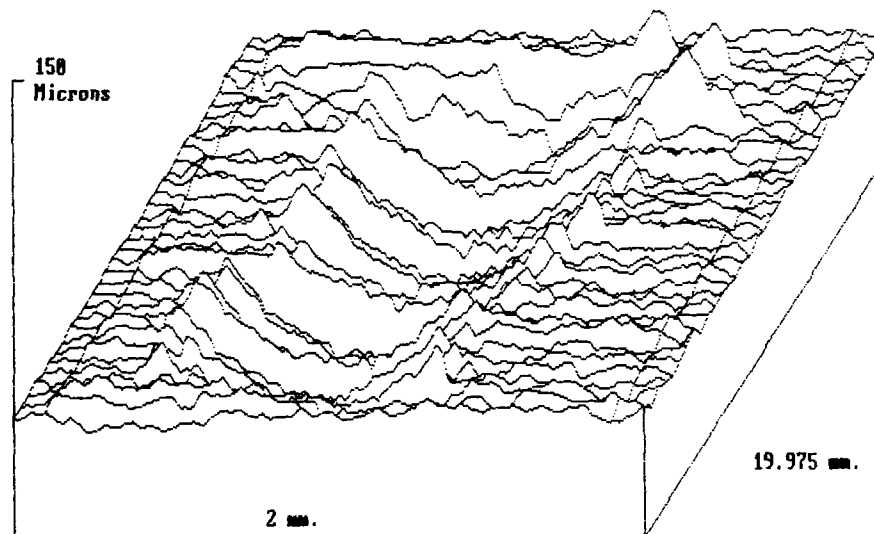
Wear volume in cubic millimetres

Above datum	Below datum	Net loss
2.866068E-02	.255984	.2273234

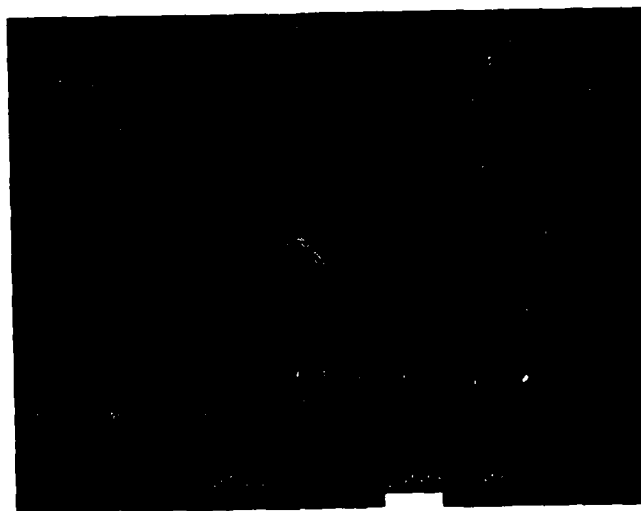


# HSSA 10: Hard Anodised 3

Data from h:hssa10.dat  
Detrended

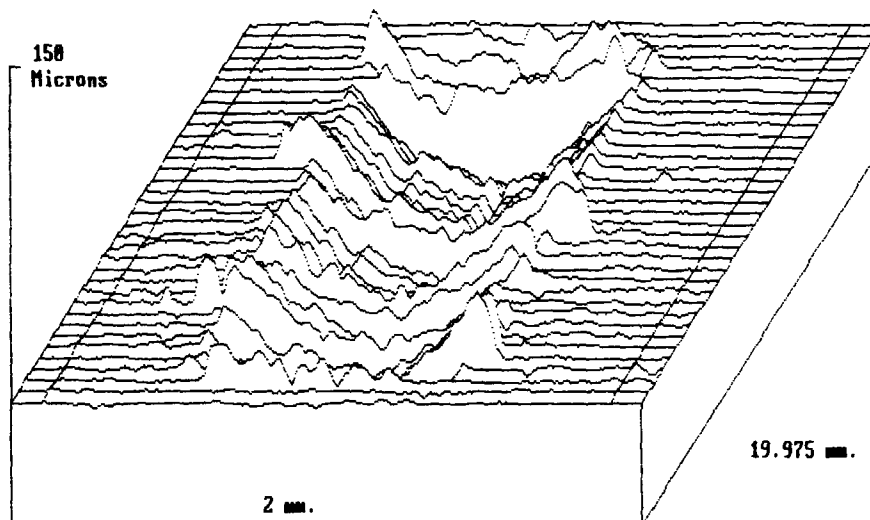


Wear volume in cubic millimetres .  
Above datum      Below datum      Net loss  
3.669301E-02      .2553586      .2186656

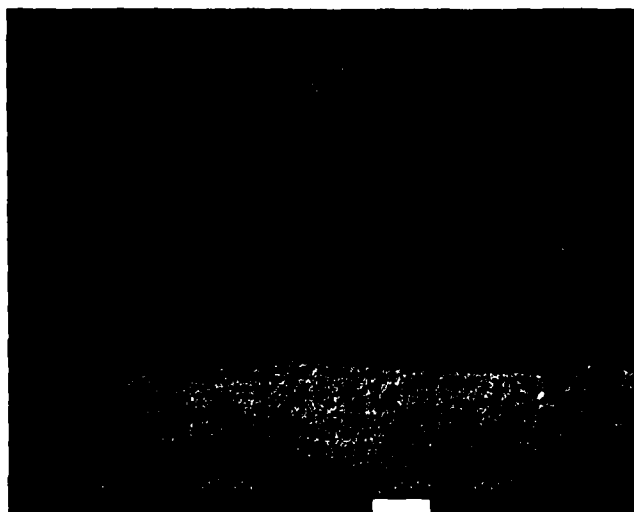


# HSSA 11: Hard Anodised 4

Data from b:hssa11.dat  
Detrended

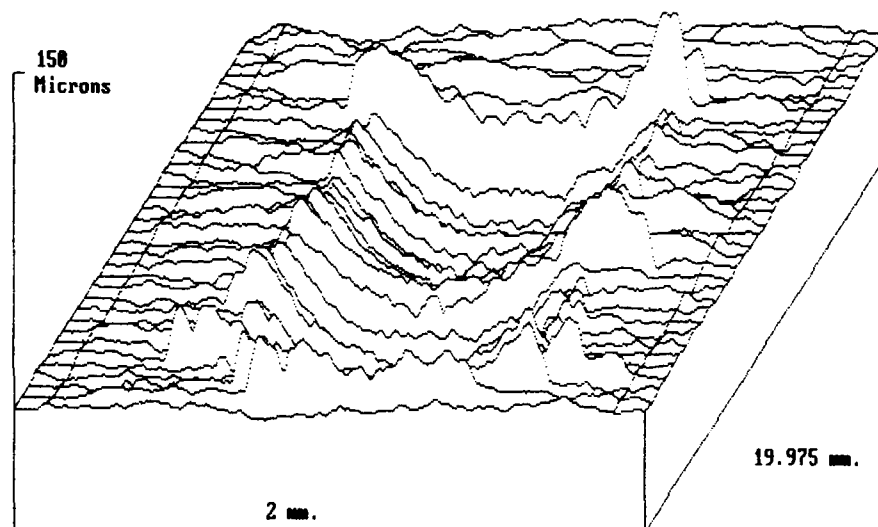


Wear volume in cubic millimetres  
Above datum    Below datum    Net loss  
2.775977E-02    .1922235    .1644637

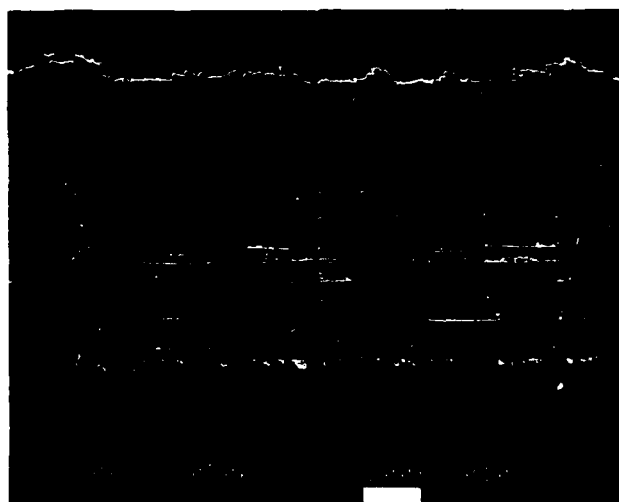


# HSSA 12: Plasma Nitrided 1

Data from h:hssa12.dat  
Detrended

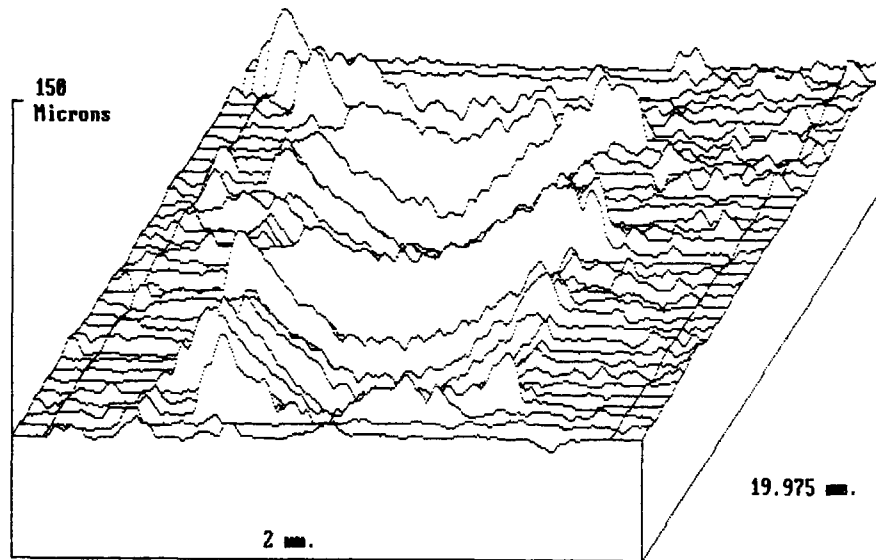


Wear volume in cubic millimetres  
Above datum    Below datum    Net loss  
5.554843E-02    .2511673    .1956188



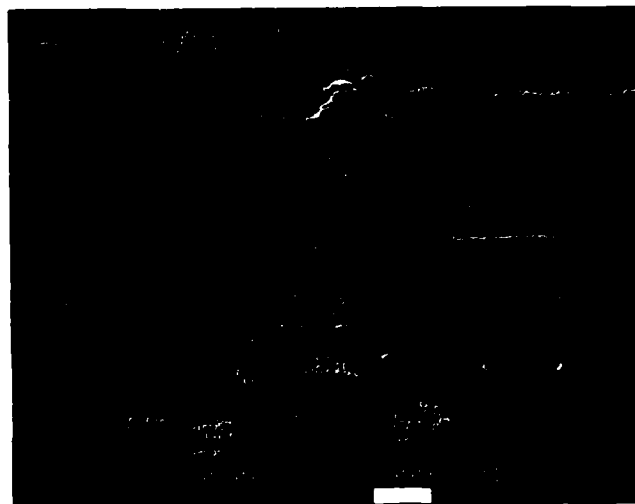
# HSSA13: Plasma Nitrided 2

Data from b:hssa13.dat  
Detrended



Wear volume in cubic millimetres

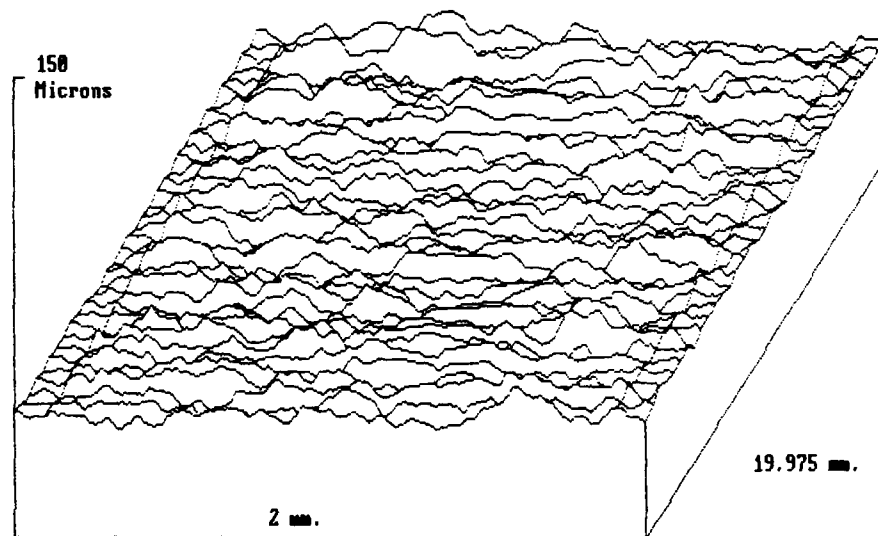
Above datum	Below datum	Net loss
4.008345E-02	.2619238	.2218404



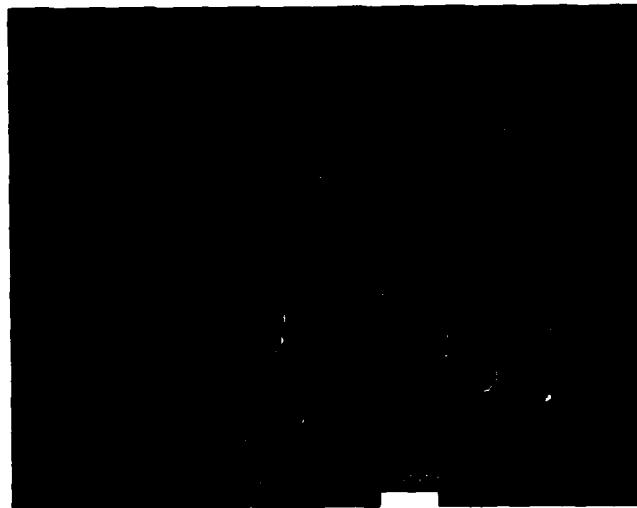


# HSSA14: High Temperature Nitrocarburized 1

Data from h:hssa14.dat  
Detrended

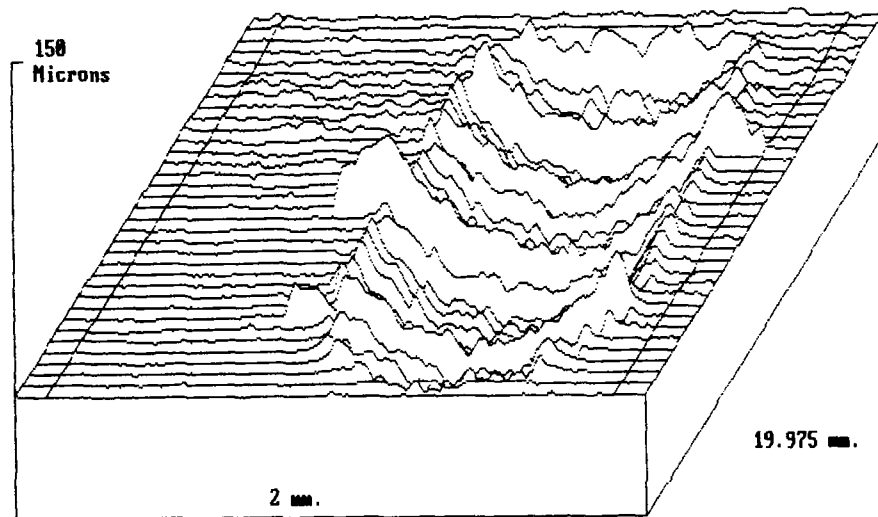


Wear volume in cubic millimetres  
Above datum    Below datum    Net loss  
4.902035E-02    4.254118E-02    -6.47917E-03

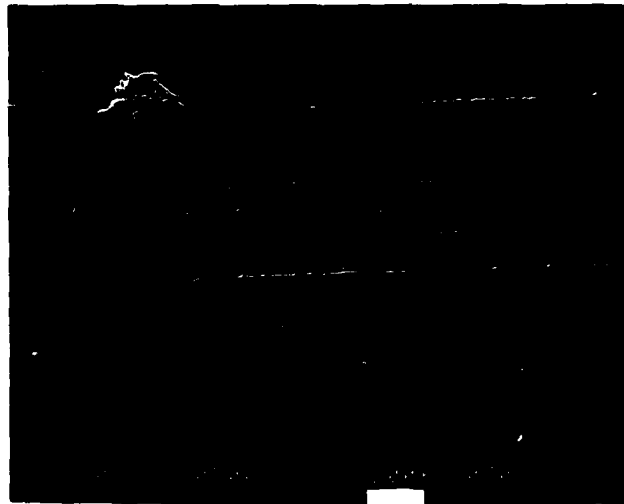


HSSA 15: Nitrox 1

Data from b:hssa15.dat  
Detrended



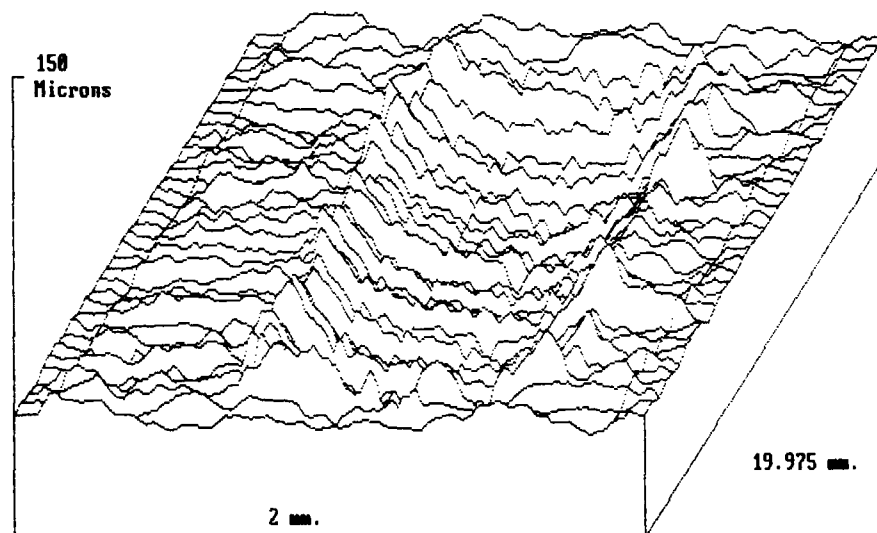
Wear volume in cubic millimetres  
Above datum    Below datum    Net loss  
1.879978E-02    .2240438    .205244



# HSSA17: Nitrosc 2

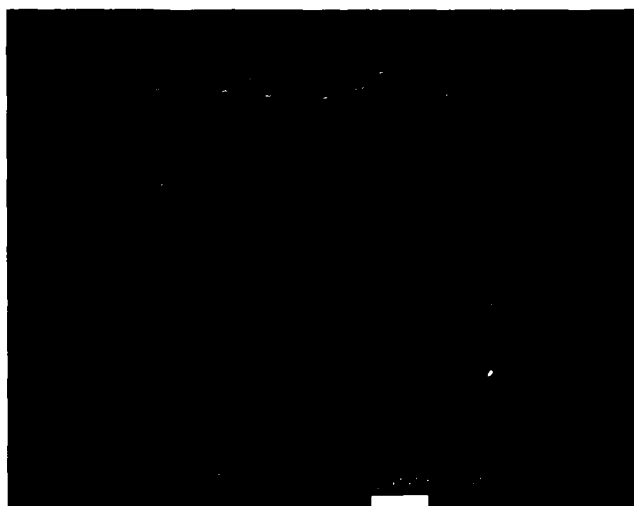
Data from b:hssa17.dat

Detrended



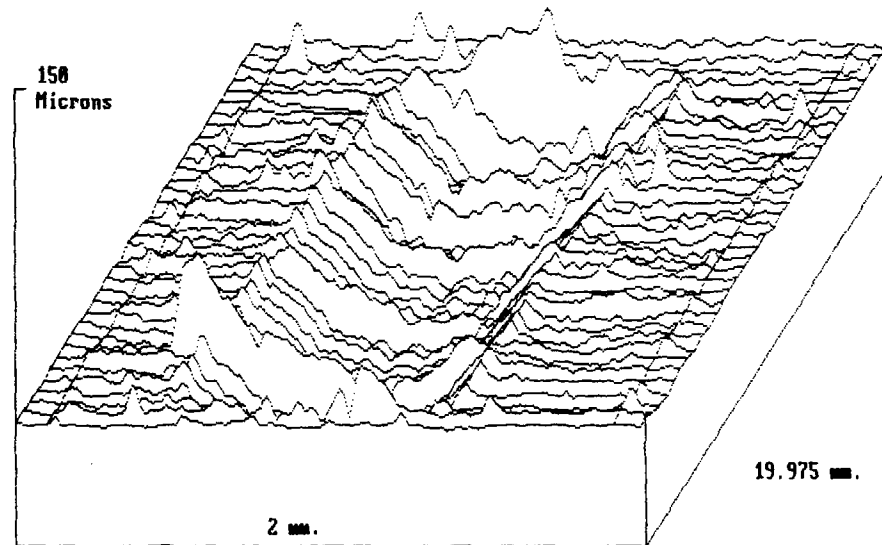
Wear volume in cubic millimetres

Above datum	Below datum	Net loss
4.378364E-02	.2352955	.1915119



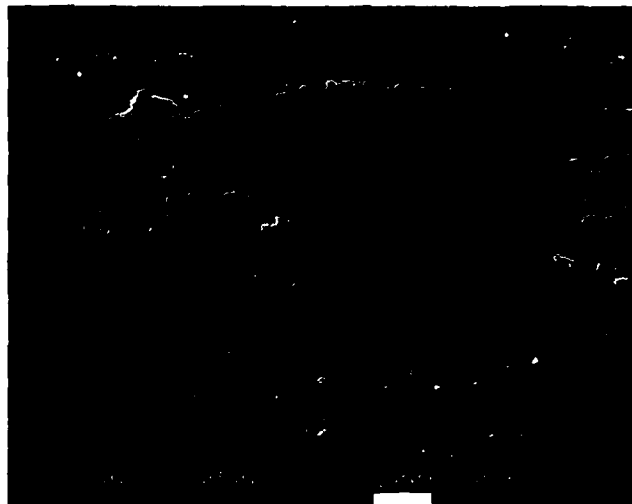
# HSSA 18: Nitrosc 3

Data from h:hssa18.dat  
Detrended



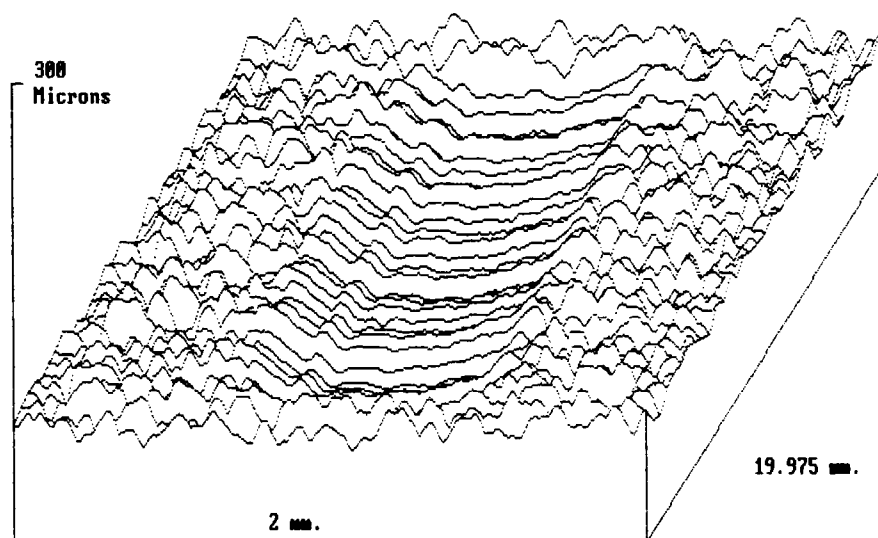
Wear volume in cubic millimetres

Above datum	Below datum	Net loss
2.324379E-02	.2662985	.2430547



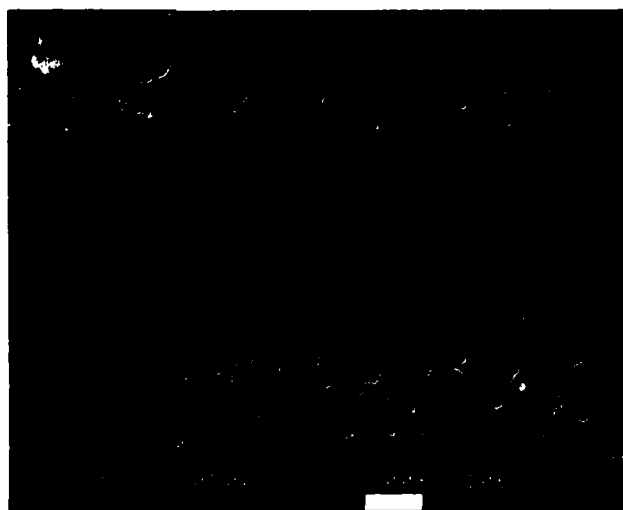
## HSSA19: Pack Aluminising 2

Data from h:hssa19.dat  
Detrended



Wear volume in cubic millimetres

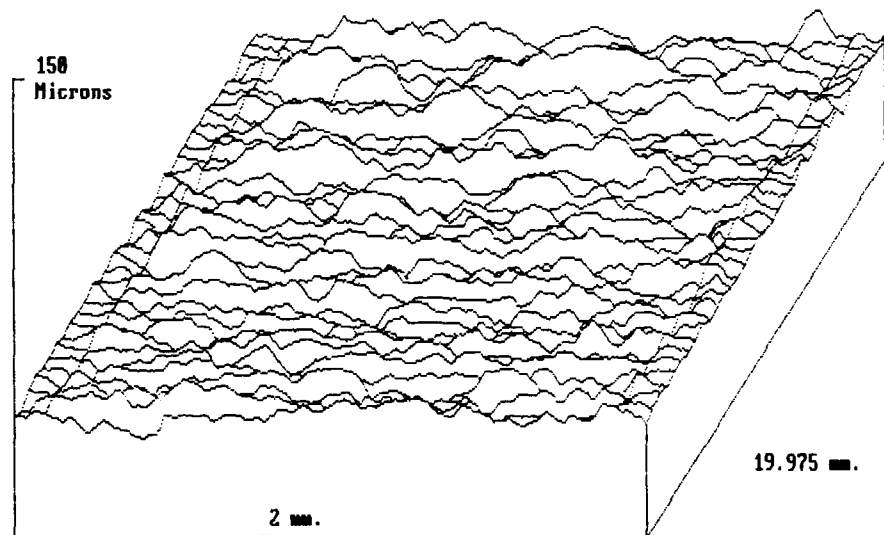
Above datum	Below datum	Net loss
7.481752E-02	.3003084	.2254909



# HSSA 20: Gas Carbonitriding 1

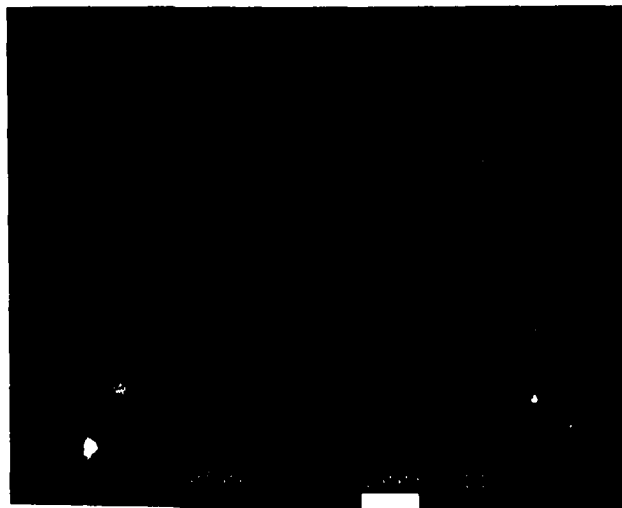
Data from b:hssa20.dat

Detrended



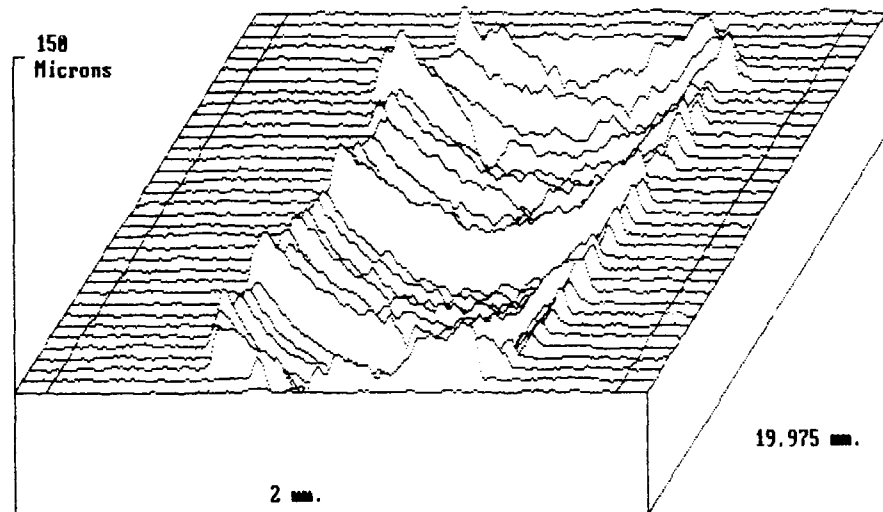
Wear volume in cubic millimetres

Above datum	Below datum	Net loss
4.566613E-02	5.848346E-02	1.281733E-02



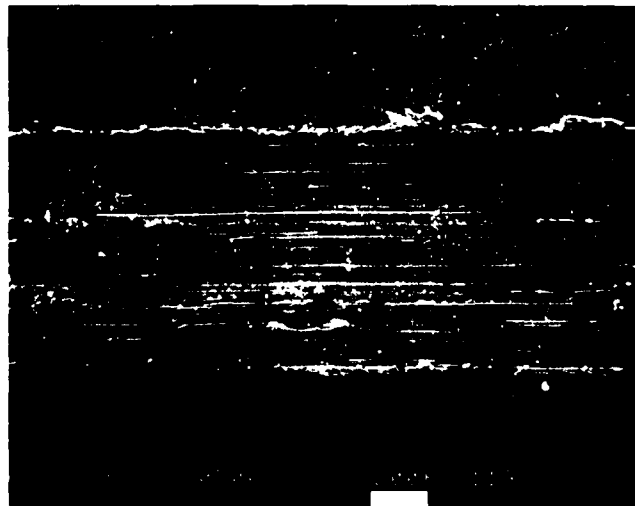
# HSSA 21: Diamond-like Carbon 1

Data from b:hssa21.dat  
Detrended



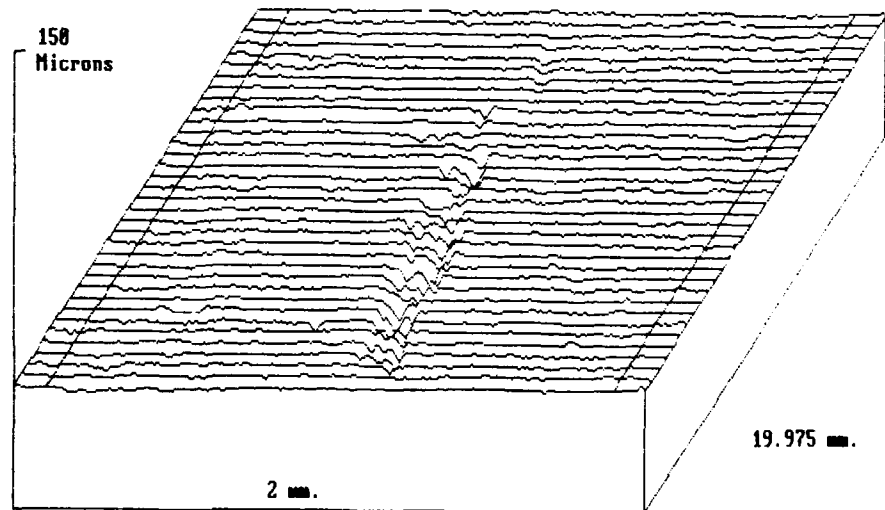
Wear volume in cubic millimetres

Above datum	Below datum	Net loss
2.667136E-02	.2495293	.222858



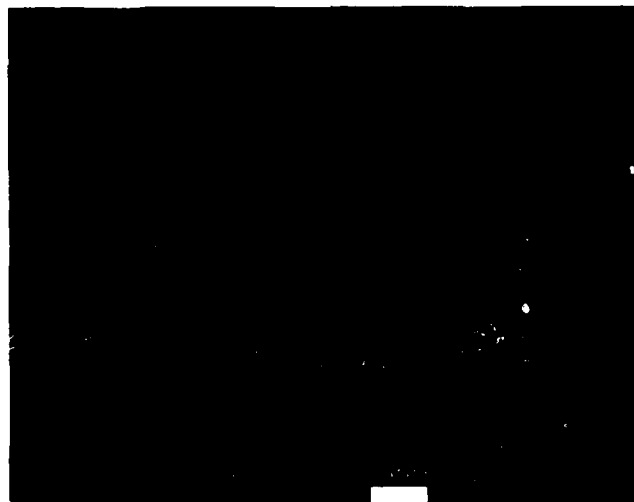
## HSSA 22: TiN Reactive Sputter

Data from h:hssa22.dat  
Detrended



Wear volume in cubic millimetres

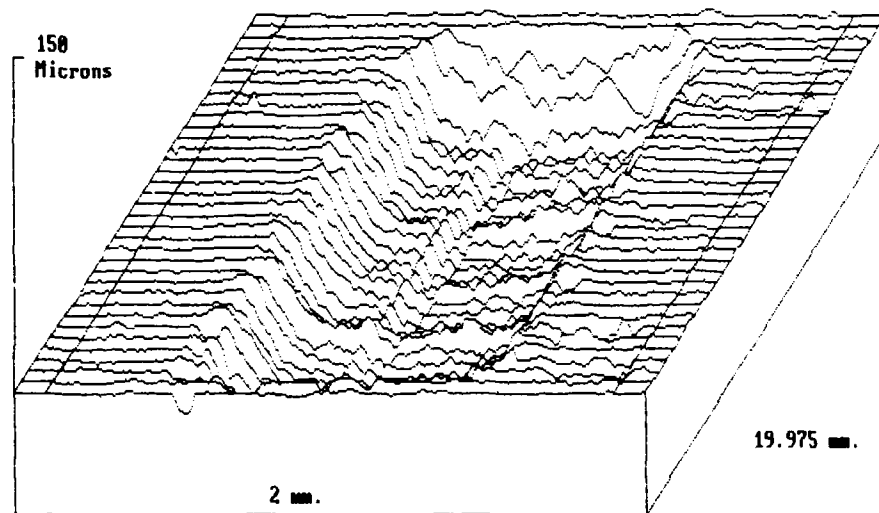
Above datum	Below datum	Net loss
3.728391E-03	1.470531E-02	1.097641E-02





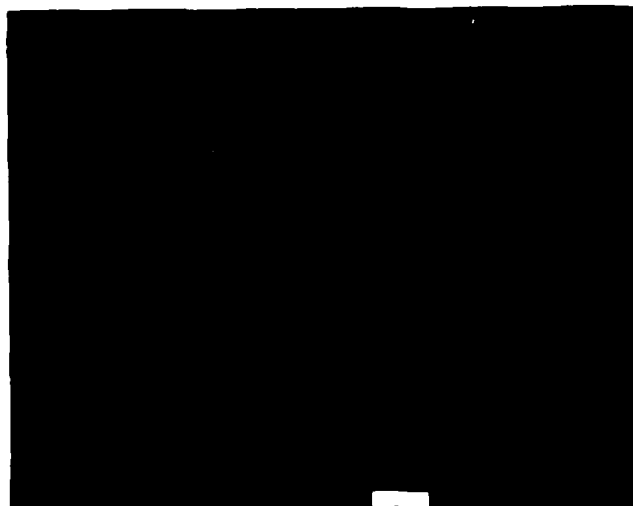
# HSSA 23: TiN/HfN Multilayer

Data from h:hssa23.dat  
Detrended



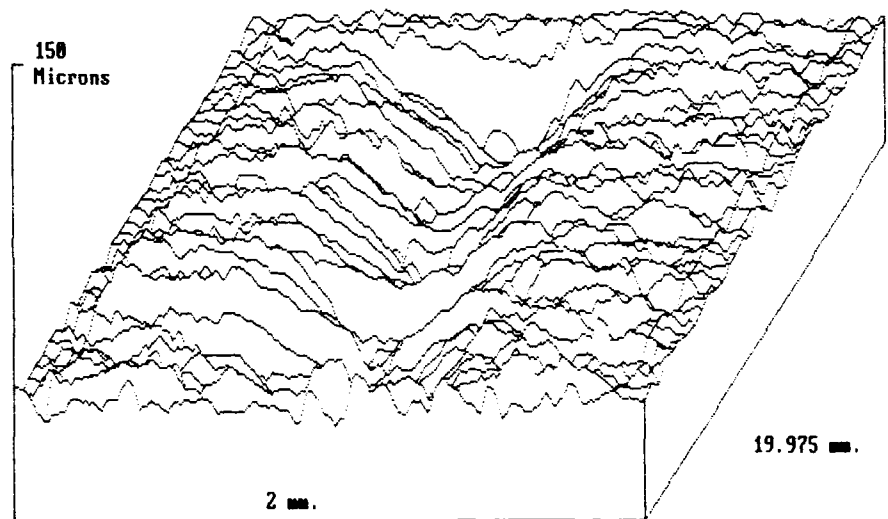
Wear volume in cubic millimetres

Above datum	Below datum	Net loss
4.79215E-03	.3629499	.3581578



# HSSA 24: Pack Aluminising 3

Data from b:hssa24.dat  
Detrended



Wear volume in cubic millimetres

Above datum	Below datum	Net loss
5.017138E-02	.2289717	.1788003

